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INTERGOVERNMENTAL PANEL ON climate change

CLIMATE CHANGE 2014

Impacts, Adaptation, and Vulnerability

Part A: Global and Sectoral Aspects

WG II

WORKING GROUP II CONTRIBUTION TO THE
FIFTH ASSESSMENT REPORT OF THE
INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

WMO UNEP

Climate Change 2014
Impacts, Adaptation, and Vulnerability
Part A: Global and Sectoral Aspects

Working Group II Contribution to the
Fifth Assessment Report of the
Intergovernmental Panel on Climate Change

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32 Avenue of the Americas, New York, NY 10013-2473, USA

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781107641655

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First published 2014

Printed in the United States of America

A catalog record for this publication is available from the British Library.

ISBN 978-1-107-05807-1 Hardback
ISBN 978-1-107-64165-5 Paperback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party Internet Web sites referred to in this publication and does not guarantee that any content on such Web sites is, or will remain, accurate or appropriate.

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Use the following reference to cite Part A:

IPCC, 2014: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp.

Cover Photo:

Planting of mangrove seedlings in Funafala, Funafuti Atoll, Tuvalu. © David J. Wilson

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Foreword, Preface, and Dedication

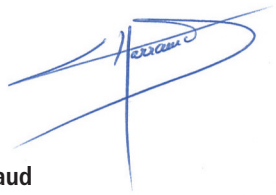
Foreword

Climate Change 2014: Impacts, Adaptation, and Vulnerability is the second volume of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) — *Climate Change 2013/2014* — and was prepared by its Working Group II. The volume focuses on why climate change matters and is organized into two parts, devoted respectively to human and natural systems and regional aspects, incorporating results from the reports of Working Groups I and III. The volume addresses impacts that have already occurred and risks of future impacts, especially the way those risks change with the amount of climate change that occurs and with investments in adaptation to climate changes that cannot be avoided. For both past and future impacts, a core focus of the assessment is characterizing knowledge about vulnerability, the characteristics and interactions that make some events devastating, while others pass with little notice.

Three elements are new in this assessment. Each contributes to a richer, more nuanced understanding of climate change in its real-world context. The first new element is a major expansion of the topics covered in the assessment. In moving from 20 chapters in the AR4 to 30 in the AR5, the Working Group II assessment makes it clear that expanding knowledge about climate change and its impacts mandates attention to more sectors, including sectors related to human security, livelihoods, and the oceans. The second new element is a pervasive focus on risk, where risk captures the combination of uncertain outcomes and something of value at stake. A framing based on risk provides a framework for utilizing information on the full range of possible outcomes, including not only most likely outcomes but also low probability but high consequence events. The third new element is solid grounding in the evidence that impacts of climate change typically involve a number of interacting factors, with climate change adding new dimensions and complications. The implication is that understanding the impacts of climate change requires a very broad perspective.

The IPCC was established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) in 1988, with the mandate to provide the world community with the most up-to-date and comprehensive scientific, technical, and socio-economic information about climate change. The IPCC assessments have since then played a major role in motivating governments to adopt and implement policies in responding to climate change, including the United Nations Framework Convention on Climate Change and the Kyoto Protocol. IPCC's AR5 provides an important foundation of information for the world's policymakers, to help them respond to the challenge of climate change.

The *Impacts, Adaptation, and Vulnerability* report was made possible thanks to the commitment and voluntary labor of a large number of leading scientists. We would like to express our gratitude to all Coordinating Lead Authors, Lead Authors, Contributing Authors, Review Editors, and Reviewers. We would also like to thank the staff of the Working Group II Technical Support Unit and the IPCC Secretariat for their dedication in organizing the production of a very successful IPCC report. Furthermore, we would like to express our thanks to Dr. Rajendra K. Pachauri, Chairman of the IPCC, for his patient and constant guidance through the process, and to Drs. Vicente Barros and Chris Field, Co-Chairs of Working Group II, for their skillful leadership. We also wish to acknowledge and thank those governments and institutions that contributed to the IPCC Trust Fund and supported the participation of their resident scientists in the IPCC process. We would like to mention in particular the Government of the United States of America, which funded the Technical Support Unit; the Government of Japan, which hosted the plenary session for the approval of the report; and the Governments of Japan, United States of America, Argentina, and Slovenia, which hosted the drafting sessions to prepare the report.



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Preface

The Working Group II contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC WGII AR5) considers climate change impacts, adaptation, and vulnerability. It provides a comprehensive, up-to-date picture of the current state of knowledge and level of certainty, based on the available scientific, technical, and socio-economic literature. As with all IPCC products, the report is the result of an assessment process designed to highlight both big-picture messages and key details, to integrate knowledge from diverse disciplines, to evaluate the strength of evidence underlying findings, and to identify topics where understanding is incomplete. The focus of the assessment is providing information to support good decisions by stakeholders at all levels. The assessment is a unique source of background for decision support, while scrupulously avoiding advocacy for particular policy options.

Scope of the Report

Climate change impacts, adaptation, and vulnerability span a vast range of topics. With the deepening of knowledge about climate change, we see connections in expanding and diverse areas, activities, and assets at risk. Early research focused on direct impacts of temperature and rainfall on humans, crops, and wild plants and animals. New evidence points to the importance of understanding not only these direct impacts but also potential indirect impacts, including impacts that can be transmitted around the world through trade, travel, and security. As a consequence, few aspects of the human endeavor or of natural ecosystem processes are isolated from possible impacts in a changing climate. The interconnectedness of the Earth system makes it impossible to draw a confined boundary around climate change impacts, adaptation, and vulnerability. This report does not attempt to bound the issue. Instead, it focuses on core elements and identifies connecting points where the issue of climate change overlaps with or merges into other issues.

The integrative nature of the climate change issue underlies three major new elements of the WGII contribution to the AR5. The first is explicit coverage of a larger range of topics, with new chapters. Increasing knowledge, expressed in a rapidly growing corpus of published literature, enables deeper assessment in a number of areas. Some of these are geographic, especially the addition of two chapters on oceans. Other new chapters further develop topics covered in earlier assessments, reflecting the increased sophistication of the available research. Expanded coverage of human settlements, security, and livelihoods builds on new research concerning human dimensions of climate change. A large increase in the published literature on adaptation motivates assessment in a suite of chapters.

A second new emphasis is the focus on climate change as a challenge in managing and reducing risk, as well as capitalizing on opportunities. There are several advantages to understanding the risk of impacts from climate change as resulting from the overlap of hazards from the physical climate and the vulnerability and exposure of people, ecosystems, and assets. Some of the advantages accrue from the opportunity to evaluate factors that regulate each component of risk. Others relate to the way that a focus on risk can clarify bridges to solutions. A focus on risk can link historical experience with future projections. It helps integrate the role of extremes. And it highlights the importance of considering the full range of possible outcomes, while opening the door to a range of tools relevant to decision making under uncertainty.

A third new emphasis ties together the interconnectedness of climate change with a focus on risk. Risks of climate change unfold in environments with many interacting processes and stressors. Often, climate change acts mainly through adding new dimensions and complications to sometimes longstanding challenges. Appreciating the multi-stressor context of the risks of climate change can open doors to new insights and approaches for solutions.

Increased knowledge of the risks of climate change can be a starting point for understanding the opportunities for and implications of possible solutions. Some of the solution space is in the domain of mitigation, extensively covered by the Working Group III contribution to the AR5. The WGII AR5 delves deep into adaptation. But many opportunities exist in linking climate change adaptation, mitigation, and sustainable development. In contrast to past literature that tended to characterize adaptation, mitigation, and sustainable development as competing agendas, new literature identifies complementarities. It shines light on options for leveraging investments in managing and reducing the risks of climate change to enable vibrant communities, robust economies, and healthy ecosystems, in all parts of the world.

Structure of the Report

The Working Group II contribution to the IPCC Fifth Assessment Report consists of a brief summary for policymakers, a longer technical summary, and 30 thematic chapters, plus supporting annexes. A series of cross-chapter boxes and a collection of Frequently Asked Questions provide an integrated perspective on selected key issues. Electronic versions of all the printed contents, plus supplemental online material, are available at no charge at www.ipcc.ch.

The report is published in two parts. Part A covers global-scale topics for a wide range of sectors, covering physical, biological, and human systems. Part B considers the same topics, but from a regional perspective, exploring the issues that arise from the juxtaposition of climate change, environment, and available resources. Conceptually, there is some overlap between the material in Parts A and B, but the contrast in framing makes each part uniquely relevant to a particular group of stakeholders. For setting context and meeting the needs of users focused on regional-scale issues, Part B extracts selected materials from the Working Group I and Working Group III contributions to the Fifth Assessment Report. To acknowledge the different purposes for the two parts and the balanced contributions of the co-chairs, the listing order of the editors differs between the two parts, with Chris Field listed first on Part A and Vicente Barros listed first on Part B.

The 20 chapters in Part A are arranged in six thematic groups.

Context for the AR5

The two chapters in this group, (1) Point of departure and (2) Foundations for decision making, briefly summarize the conclusions of the Fourth Assessment Report and the Working Group I contribution to the AR5. They explain the motivation for the focus on climate change as a challenge in managing and reducing risks and assess the relevance of diverse approaches to decision making in the context of climate change.

Natural and Managed Resources and Systems, and Their Uses

The five chapters in this group, (3) Freshwater resources, (4) Terrestrial and inland water systems, (5) Coastal systems and low-lying areas, (6) Ocean systems, and (7) Food security and food production systems, cover diverse sectors, with a new emphasis on resource security. The ocean systems chapter, focused on the processes at work in ocean ecosystems, is a major element of the increased coverage of oceans in the WGII AR5.

Human Settlements, Industry, and Infrastructure

The three chapters in this group, (8) Urban areas, (9) Rural areas, and (10) Key economic sectors and services, provide expanded coverage of settlements and economic activity. With so many people living in and moving to cities, urban areas are increasingly important in understanding the climate change issue.

Human Health, Well-Being, and Security

The three chapters in this group, (11) Human health: impacts, adaptation, and co-benefits, (12) Human security, and (13) Livelihoods and poverty, increase the focus on people. These chapters address a wide range of processes, from vector-borne disease through conflict and migration. They assess the relevance of local and traditional knowledge.

Adaptation

An expanded treatment of adaptation is one of the signature changes in the WGII AR5. Chapters treat (14) Adaptation needs and options, (15) Adaption planning and implementation, (16) Adaptation opportunities, constraints, and limits, and (17) Economics of adaptation. This coverage reflects a large increase in literature and the emergence of climate-change adaptation plans in many countries and concrete action in some.

Multi-Sector Impacts, Risks, Vulnerabilities, and Opportunities

The three chapters in this group, (18) Detection and attribution of observed impacts, (19) Emergent risks and key vulnerabilities, and (20) Climate-resilient pathways: adaptation, mitigation, and sustainable development, collect material from the chapters in both Parts A and B to provide a sharp focus on aspects of climate change that emerge only by examining many examples across the regions of the Earth and the entirety of the human endeavor. These chapters provide an integrative view of three central questions related to understanding risks in a changing climate – what are the impacts to date (and how certain is the link to climate change), what are the most important risks looking forward, and what are the opportunities for linking responses to climate change with other societal goals.

The 10 chapters in Part B start with a chapter, (21) Regional context, structured to help readers understand and capitalize on regional information. It is followed by chapters on 9 world regions: (22) Africa, (23) Europe, (24) Asia, (25) Australasia, (26) North America, (27) Central and South America, (28) Polar regions, (29) Small islands, and (30) The ocean (taking a regional cut through ocean issues, including human utilization of ocean resources). Each chapter in this part is an all-in-one resource for regional stakeholders, while also contributing to and building from the global assessment. Regional climate-change maps, which complement the Working Group I Atlas of Global and Regional Climate Projections, and quantified key regional risks are highlights of these chapters. Each chapter explores the issues and themes that are most relevant in the region.

Process

The Working Group II contribution to the IPCC Fifth Assessment Report was prepared in accordance with the procedures of the IPCC. Chapter outlines were discussed and defined at a scoping meeting in Venice in July 2009, and outlines for the three Working Group contributions were approved at the 31st session of the Panel in November 2009, in Bali, Indonesia. Governments and IPCC observer organizations nominated experts for the author team. The team of 64 Coordinating Lead Authors, 179 Lead Authors, and 66 Review Editors was selected by the WGII Bureau and accepted by the IPCC Bureau in May 2010. More than 400 Contributing Authors, selected by the chapter author teams, contributed text.

Drafts prepared by the author teams were submitted for two rounds of formal review by experts, of which one was also a review by governments. Author teams revised the draft chapters after each round of review, with Review Editors working to assure that every review comment was fully considered, and where appropriate, chapters were adjusted to reflect points raised in the reviews. In addition, governments participated in a final round of review of the draft Summary for Policymakers. All of the chapter drafts, review comments, and author responses are available online via www.ipcc.ch. Across all of the drafts, the WGII contribution to the AR5 received 50,492 comments from 1,729 individual expert reviewers from 84 countries. The Summary for Policymakers was approved line-by-line by the Panel, and the underlying chapters were accepted at the 10th Session of IPCC Working Group II and the 38th Session of the IPCC Panel, meeting in Yokohama, Japan, from March 25-30, 2014.

Acknowledgments

For the AR5, Working Group II had an amazing author team. In many ways, the author team encompasses the entire scientific community, including scientists who conducted the research and wrote the research papers on which the assessment is based, and the reviewers who contributed their wisdom in more than 50,000 review comments. But the process really ran on the sophistication, wisdom, and dedication of the 309 individuals from 70 countries who comprise the WGII team of Coordinating Lead Authors, Lead Authors, and Review Editors. These individuals, with the support of a talented group of volunteer chapter scientists and the assistance of scores of contributing authors, demonstrated an inspirational commitment to scientific quality and public service. Tragically, three of our most experienced authors passed away while the report was being written. We greatly miss JoAnn Carmin, Abby Sallenger, and Steve Schneider.

We benefitted greatly from the advice and guidance of the Working Group II Bureau: Amjad Abdulla (Maldives), Eduardo Calvo Buendía (Peru), José M. Moreno (Spain), Nirivololona Raholijao (Madagascar), Sergey Semenov (Russian Federation), and Neville Smith (Australia). Their understanding of regional resources and concerns has been invaluable.

Throughout the AR5, we benefitted greatly from the wisdom and insight of our colleagues in the IPCC leadership, especially the IPCC chair, R.K. Pachauri. All of the members of the IPCC Executive Committee worked effectively and selflessly on issues related to the reports from all three working groups. We extend a heartfelt thanks to all of the members of the ExCom: R.K. Pachauri, Ottmar Edenhofer, Ismail El Gizouli, Taka Hiraishi, Thelma Krug, Hoesung Lee, Ramón Pichs Madruga, Qin Dahe, Youba Sokona, Thomas Stocker, and Jean-Pascal van Ypersele.

We are very appreciative of the enthusiastic cooperation of the nations that hosted our excellent working meetings, including four lead author meetings and the 10th Session of Working Group II. We gratefully acknowledge the support of the governments of Japan, the United States, Argentina, and Slovenia for hosting the lead author meetings, and the government of Japan for hosting the approval session. The government of the United States provided essential financial support for the Working Group II Technical Support Unit. Special thanks to the principals of the United States Global Change Research Program for orchestrating the funding across many research agencies.

We want very much to thank the staff of the IPCC Secretariat: Renate Christ, Gaetano Leone, Carlos Martin-Novella, Jonathan Lynn, Brenda Abrar-Milani, Jesbin Baidya, Laura Biagioni, Mary Jean Burer, Annie Courtin, Judith Ewa, Joelle Fernandez, Nina Peeva, Sophie Schlingemann, Amy Smith, and Werani Zabula. Thanks to Francis Hayes who served as conference officer for the approval session. Thanks to the individuals who coordinated the organization for each of the lead authors meetings. This was Mizue Yuzurihara and Claire Summers for LAM1, Sandy MacCracken for LAM2, Ramiro Saurral for LAM3, and Mojca Deželak for LAM4. Students from Japan, the United States, Argentina, and Slovenia helped with the lead author meetings.

The WGII Technical Support Unit was fabulous. They combined scientific sophistication, technical excellence, artistic vision, deep resilience, and profound dedication, not to mention a marked ability to compensate for oversights by and deficiencies of the co-chairs. Dave Dokken, Mike Mastrandrea, Katie Mach, Kris Ebi, Monalisa Chatterjee, Sandy MacCracken, Eric Kissel, Yuka Estrada, Leslie White, Eren Bilir, Rob Genova, Beti Girma, Andrew Levy, and Patricia Mastrandrea have all made wonderful contributions to the report. In addition, the work of David Ropeik (frequently asked questions), Marcos Senet (assistant to Vicente Barros), Terry Kornak (technical edits), Marilyn Anderson (index), Liu Yingjie (Chinese author support), and Janak Pathak (UNEP communications) made a big difference. Kyle Terran, Gete Bond, and Sandi Fikes facilitated travel. Volunteer contributions from John Kelley and Ambarish Malpani greatly enhanced reference management. Catherine Lemmi, Ian Sparkman, and Danielle Olivera were super interns.

We extend a deep, personal thanks to our families and to the families of every author and reviewer. We know you tolerated many late nights and weekends with partners, parents, or children sitting at the computer or mumbling about one more assignment from us.



Vicente Barros
IPCC WGII Co-Chair



Chris Field
IPCC WGII Co-Chair

Dedication



Credit: Odd-Steinar Tøllefsen

Yuri Antonievich Izrael
(15 May 1930 to 23 January 2014)

The Working Group II contribution to the IPCC Fifth Assessment Report is dedicated to the memory of Professor Yuri Antonievich Izrael, first Chair of Working Group II from 1988 to 1992 and IPCC Vice Chair from 1992 to 2008. Professor Izrael was a pioneer, opening doors that have allowed thousands of scientists to contribute to the work of the IPCC.

Through a long and distinguished career, Professor Izrael was a strong proponent of environmental sciences, meteorology, climatology, and international organizations, especially the IPCC and the World Meteorological Organization. A creative researcher and tireless institution builder, Dr. Izrael founded and for more than two decades led the Institute of Global Climate and Ecology.

In the IPCC, Professor Izrael played a central role in creating the balance of IPCC efforts on careful observations, mechanisms, and systematic projections using scenarios. An outspoken advocate for the robust integration of scientific excellence and broad participation in IPCC reports, Dr. Izrael pioneered many of the features that assure the comprehensiveness and integrity of IPCC reports.

Summary for Policymakers

SPM

Summary for Policymakers

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This Summary for Policymakers should be cited as:
IPCC, 2014: Summary for policymakers. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.

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ASSESSING AND MANAGING THE RISKS OF CLIMATE CHANGE

Human interference with the climate system is occurring,[1] and climate change poses risks for human and natural systems (Figure SPM.1). The assessment of impacts, adaptation, and vulnerability in the Working Group II contribution to the IPCC's Fifth Assessment Report (WGII AR5) evaluates how patterns of risks and potential benefits are shifting due to climate change. It considers how impacts and risks related to climate change can be reduced and managed through adaptation and mitigation. The report assesses needs, options, opportunities, constraints, resilience, limits, and other aspects associated with adaptation.

Climate change involves complex interactions and changing likelihoods of diverse impacts. A focus on risk, which is new in this report, supports decision making in the context of climate change and complements other elements of the report. People and societies may perceive or rank risks and potential benefits differently, given diverse values and goals.

Compared to past WGII reports, the WGII AR5 assesses a substantially larger knowledge base of relevant scientific, technical, and socioeconomic literature. Increased literature has facilitated comprehensive assessment across a broader set of topics and sectors, with expanded coverage of human systems, adaptation, and the ocean. See Background Box SPM.1.[2]

Section A of this summary characterizes observed impacts, vulnerability and exposure, and adaptive responses to date. Section B examines future risks and potential benefits. Section C considers principles for effective adaptation and the broader interactions among adaptation, mitigation,

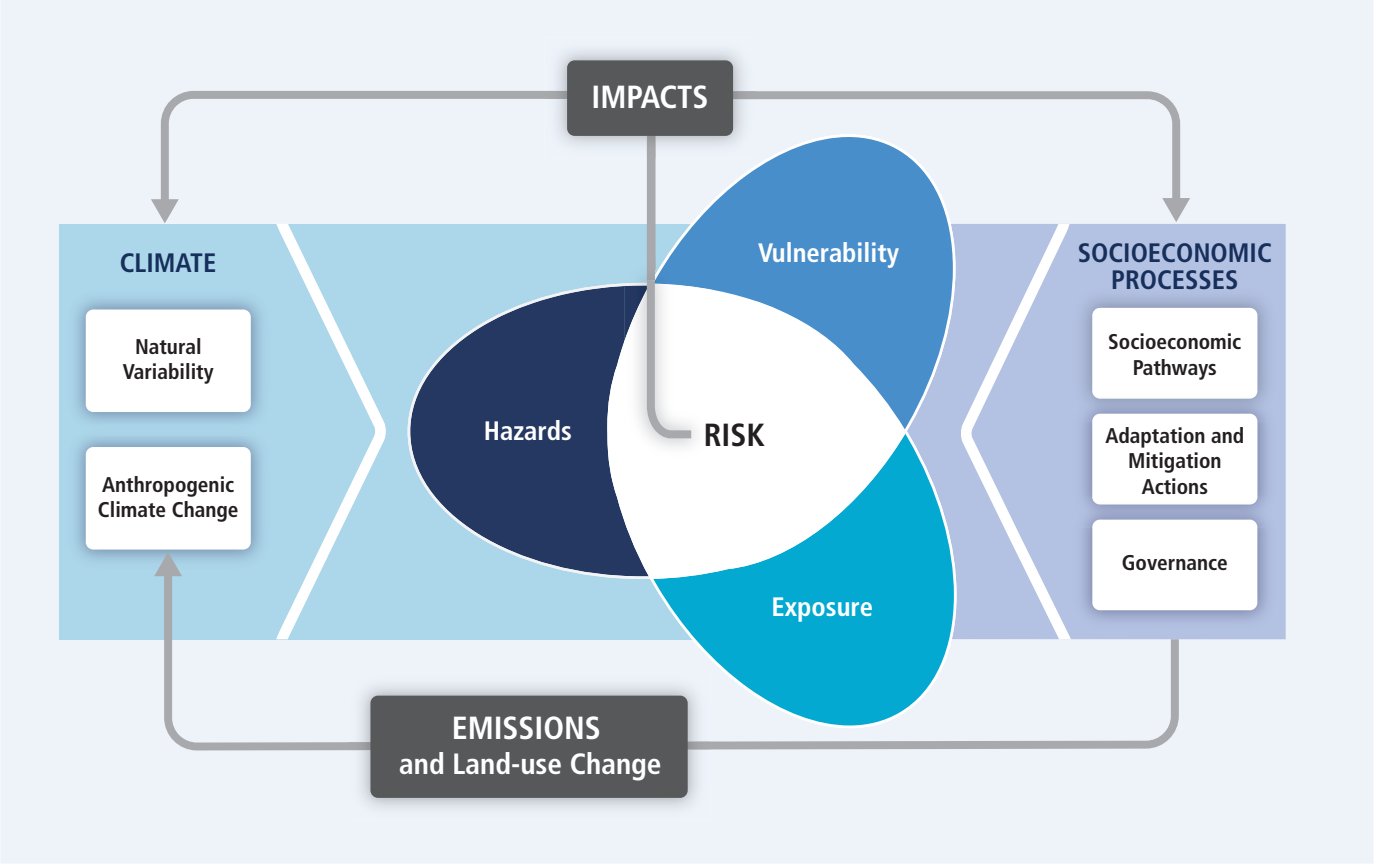


Figure SPM.1 | Illustration of the core concepts of the WGII AR5. Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems. Changes in both the climate system (left) and socioeconomic processes including adaptation and mitigation (right) are drivers of hazards, exposure, and vulnerability. [19.2, Figure 19-1]

[1] A key finding of the WGI AR5 is, "It is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century." [WGI AR5 SPM Section D.3, 2.2, 6.3, 10.3-6, 10.9]

[2] 1.1, Figure 1-1

Background Box SPM.1 | Context for the Assessment

For the past 2 decades, IPCC's Working Group II has developed assessments of climate-change impacts, adaptation, and vulnerability. The WGII AR5 builds from the WGII contribution to the IPCC's Fourth Assessment Report (WGII AR4), published in 2007, and the *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX), published in 2012. It follows the Working Group I contribution to the AR5 (WGI AR5).[3]

The number of scientific publications available for assessing climate-change impacts, adaptation, and vulnerability more than doubled between 2005 and 2010, with especially rapid increases in publications related to adaptation. Authorship of climate-change publications from developing countries has increased, although it still represents a small fraction of the total.[4]

The WGII AR5 is presented in two parts (Part A: Global and Sectoral Aspects, and Part B: Regional Aspects), reflecting the expanded literature basis and multidisciplinary approach, increased focus on societal impacts and responses, and continued regionally comprehensive coverage.

and sustainable development. Background Box SPM.2 defines central concepts, and Background Box SPM.3 introduces terms used to convey the degree of certainty in key findings. Chapter references in brackets and in footnotes indicate support for findings, figures, and tables.

A: OBSERVED IMPACTS, VULNERABILITY, AND ADAPTATION IN A COMPLEX AND CHANGING WORLD

A-1. Observed Impacts, Vulnerability, and Exposure

In recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. Evidence of climate-change impacts is strongest and most comprehensive for natural systems. Some impacts on human systems have also been attributed[5] to climate change, with a major or minor contribution of climate change distinguishable from other influences. See Figure SPM.2. Attribution of observed impacts in the WGII AR5 generally links responses of natural and human systems to observed climate change, regardless of its cause.[6]

In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality (*medium confidence*). Glaciers continue to shrink almost worldwide due to climate change (*high confidence*), affecting runoff and water resources downstream (*medium confidence*). Climate change is causing permafrost warming and thawing in high-latitude regions and in high-elevation regions (*high confidence*).[7]

Many terrestrial, freshwater, and marine species have shifted their geographic ranges, seasonal activities, migration patterns, abundances, and species interactions in response to ongoing climate change (*high confidence*). See Figure SPM.2B. While only a few recent species extinctions have been attributed as yet to climate change (*high confidence*), natural global climate change at rates slower than current anthropogenic climate change caused significant ecosystem shifts and species extinctions during the past millions of years (*high confidence*).[8]

Based on many studies covering a wide range of regions and crops, negative impacts of climate change on crop yields have been more common than positive impacts (*high confidence*). The smaller number of studies showing positive impacts relate mainly to

[3] 1.2-3
[4] 1.1, Figure 1-1
[5] The term *attribution* is used differently in WGI and WGII. Attribution in WGII considers the links between impacts on natural and human systems and observed climate change, regardless of its cause. By comparison, attribution in WGI quantifies the links between observed climate change and human activity, as well as other external climate drivers.
[6] 18.1, 18.3-6
[7] 3.2, 4.3, 18.3, 18.5, 24.4, 26.2, 28.2, Tables 3-1 and 25-1, Figures 18-2 and 26-1
[8] 4.2-4, 5.3-4, 6.1, 6.3-4, 18.3, 18.5, 22.3, 24.4, 25.6, 28.2, 30.4-5, Boxes 4-2, 4-3, 25-3, CC-CR, and CC-MB

Background Box SPM.2 | Terms Central for Understanding the Summary[9]

Climate change: Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes.

Hazard: The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In this report, the term *hazard* usually refers to climate-related physical events or trends or their physical impacts.

Exposure: The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.

Vulnerability: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Impacts: Effects on natural and human systems. In this report, the term *impacts* is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as *consequences* and *outcomes*. The impacts of climate change on geophysical systems, including floods, droughts, and sea level rise, are a subset of impacts called physical impacts.

Risk: The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure, and hazard (see Figure SPM.1). In this report, the term *risk* is used primarily to refer to the risks of climate-change impacts.

Adaptation: The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.

Transformation: A change in the fundamental attributes of natural and human systems. Within this summary, transformation could reflect strengthened, altered, or aligned paradigms, goals, or values towards promoting adaptation for sustainable development, including poverty reduction.

Resilience: The capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation.

high-latitude regions, though it is not yet clear whether the balance of impacts has been negative or positive in these regions (*high confidence*). Climate change has negatively affected wheat and maize yields for many regions and in the global aggregate (*medium confidence*). Effects on rice and soybean yield have been smaller in major production regions and globally, with a median change of zero across all available data, which are fewer for soy compared to the other crops. Observed impacts relate mainly to production aspects of food security rather than access

[9] The WGII AR5 glossary defines many terms used across chapters of the report. Reflecting progress in science, some definitions differ in breadth and focus from the definitions used in the AR4 and other IPCC reports.

Background Box SPM.3 | Communication of the Degree of Certainty in Assessment Findings[10]

The degree of certainty in each key finding of the assessment is based on the type, amount, quality, and consistency of evidence (e.g., data, mechanistic understanding, theory, models, expert judgment) and the degree of agreement. The summary terms to describe evidence are: *limited*, *medium*, or *robust*; and agreement: *low*, *medium*, or *high*.

Confidence in the validity of a finding synthesizes the evaluation of evidence and agreement. Levels of confidence include five qualifiers: *very low*, *low*, *medium*, *high*, and *very high*.

The likelihood, or probability, of some well-defined outcome having occurred or occurring in the future can be described quantitatively through the following terms: *virtually certain*, 99–100% probability; *extremely likely*, 95–100%; *very likely*, 90–100%; *likely*, 66–100%; *more likely than not*, >50–100%; *about as likely as not*, 33–66%; *unlikely*, 0–33%; *very unlikely*, 0–10%; *extremely unlikely*, 0–5%; and *exceptionally unlikely*, 0–1%. Unless otherwise indicated, findings assigned a likelihood term are associated with *high* or *very high confidence*. Where appropriate, findings are also formulated as statements of fact without using uncertainty qualifiers.

Within paragraphs of this summary, the confidence, evidence, and agreement terms given for a bold key finding apply to subsequent statements in the paragraph, unless additional terms are provided.

or other components of food security. See Figure SPM.2C. Since AR4, several periods of rapid food and cereal price increases following climate extremes in key producing regions indicate a sensitivity of current markets to climate extremes among other factors (*medium confidence*).[11]

At present the worldwide burden of human ill-health from climate change is relatively small compared with effects of other stressors and is not well quantified. However, there has been increased heat-related mortality and decreased cold-related mortality in some regions as a result of warming (*medium confidence*). Local changes in temperature and rainfall have altered the distribution of some water-borne illnesses and disease vectors (*medium confidence*).[12]

Differences in vulnerability and exposure arise from non-climatic factors and from multidimensional inequalities often produced by uneven development processes *(very high confidence*). These differences shape differential risks from climate change. See Figure SPM.1. People who are socially, economically, culturally, politically, institutionally, or otherwise marginalized are especially vulnerable to climate change and also to some adaptation and mitigation responses (*medium evidence*, *high agreement*). This heightened vulnerability is rarely due to a single cause. Rather, it is the product of intersecting social processes that result in inequalities in socioeconomic status and income, as well as in exposure. Such social processes include, for example, discrimination on the basis of gender, class, ethnicity, age, and (dis)ability.[13]

Impacts from recent climate-related extremes, such as heat waves, droughts, floods, cyclones, and wildfires, reveal significant vulnerability and exposure of some ecosystems and many human systems to current climate variability (*very high confidence*). Impacts of such climate-related extremes include alteration of ecosystems, disruption of food production and water supply, damage to infrastructure and settlements, morbidity and mortality, and consequences for mental health and human well-being. For countries at all levels of development, these impacts are consistent with a significant lack of preparedness for current climate variability in some sectors.[14]

Climate-related hazards exacerbate other stressors, often with negative outcomes for livelihoods, especially for people living in poverty (*high confidence*). Climate-related hazards affect poor people's lives directly through impacts on livelihoods, reductions in crop

[10] 1.1, Box 1-1
[11] 7.2, 18.4, 22.3, 26.5, Figures 7-2, 7-3, and 7-7
[12] 11.4-6, 18.4, 25.8
[13] 8.1-2, 9.3-4, 10.9, 11.1, 11.3-5, 12.2-5, 13.1-3, 14.1-3, 18.4, 19.6, 23.5, 25.8, 26.6, 26.8, 28.4, Box CC-GC
[14] 3.2, 4.2-3, 8.1, 9.3, 10.7, 11.3, 11.7, 13.2, 14.1, 18.6, 22.3, 25.6-8, 26.6-7, 30.5, Tables 18-3 and 23-1, Figure 26-2, Boxes 4-3, 4-4, 25-5, 25-6, 25-8, and CC-CR

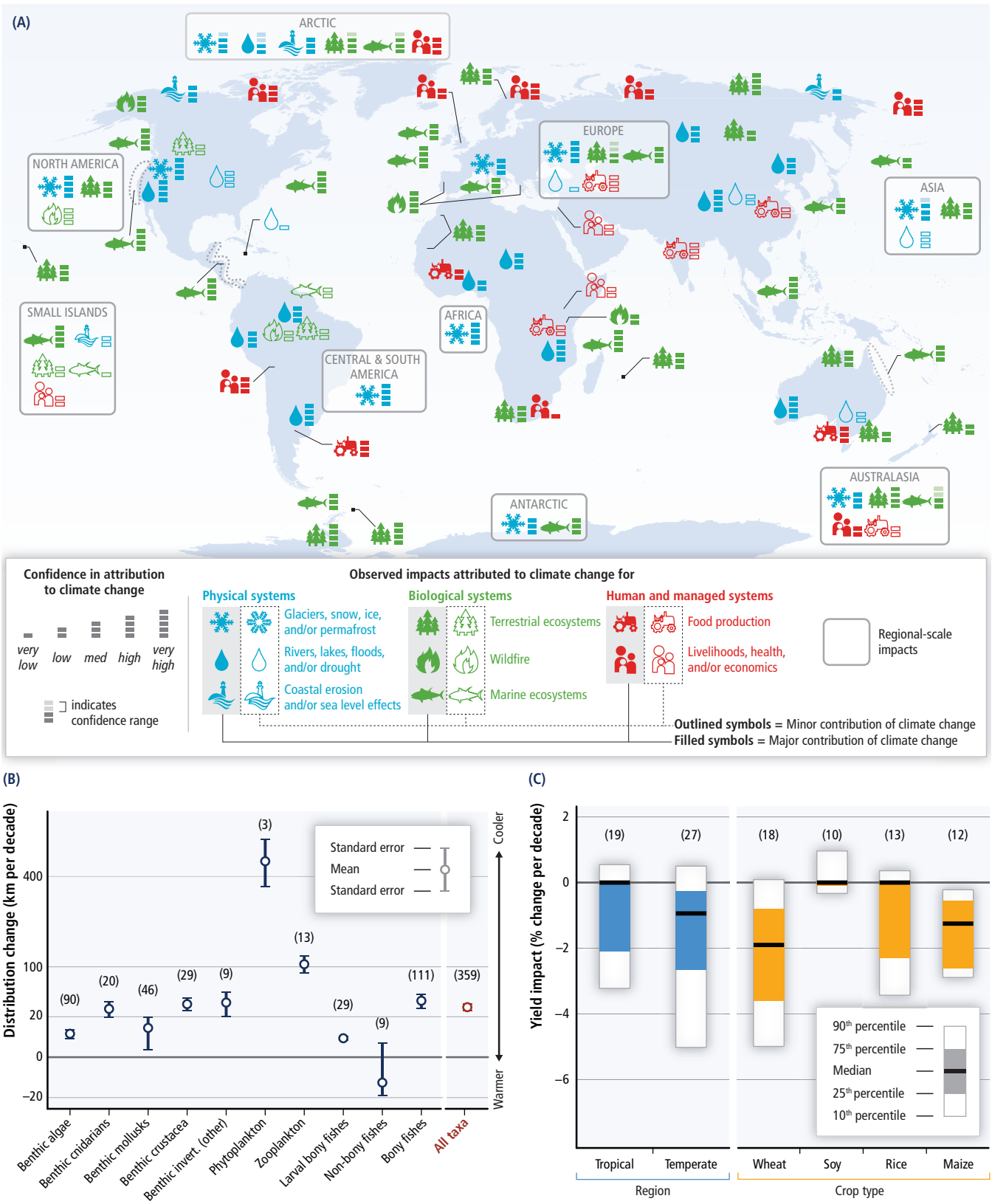


Figure SPM.2 | Widespread impacts in a changing world. (A) Global patterns of impacts in recent decades attributed to climate change, based on studies since the AR4. Impacts are shown at a range of geographic scales. Symbols indicate categories of attributed impacts, the relative contribution of climate change (major or minor) to the observed impact, and confidence in attribution. See supplementary Table SPM.A1 for descriptions of the impacts. (B) Average rates of change in distribution (km per decade) for marine taxonomic groups based on observations over 1900–2010. Positive distribution changes are consistent with warming (moving into previously cooler waters, generally poleward). The number of responses analyzed is given within parentheses for each category. (C) Summary of estimated impacts of observed climate changes on yields over 1960–2013 for four major crops in temperate and tropical regions, with the number of data points analyzed given within parentheses for each category. [Figures 7-2, 18-3, and MB-2]

yields, or destruction of homes and indirectly through, for example, increased food prices and food insecurity. Observed positive effects for poor and marginalized people, which are limited and often indirect, include examples such as diversification of social networks and of agricultural practices.[15]

Violent conflict increases vulnerability to climate change (*medium evidence*, *high agreement*). Large-scale violent conflict harms assets that facilitate adaptation, including infrastructure, institutions, natural resources, social capital, and livelihood opportunities.[16]

A-2. Adaptation Experience

Throughout history, people and societies have adjusted to and coped with climate, climate variability, and extremes, with varying degrees of success. This section focuses on adaptive human responses to observed and projected climate-change impacts, which can also address broader risk-reduction and development objectives.

Adaptation is becoming embedded in some planning processes, with more limited implementation of responses (*high confidence*). Engineered and technological options are commonly implemented adaptive responses, often integrated within existing programs such as disaster risk management and water management. There is increasing recognition of the value of social, institutional, and ecosystem-based measures and of the extent of constraints to adaptation. Adaptation options adopted to date continue to emphasize incremental adjustments and co-benefits and are starting to emphasize flexibility and learning (*medium evidence*, *medium agreement*). Most assessments of adaptation have been restricted to impacts, vulnerability, and adaptation planning, with very few assessing the processes of implementation or the effects of adaptation actions (*medium evidence*, *high agreement*).[17]

Adaptation experience is accumulating across regions in the public and private sector and within communities (*high confidence*). Governments at various levels are starting to develop adaptation plans and policies and to integrate climate-change considerations into broader development plans. Examples of adaptation across regions include the following:

- In Africa, most national governments are initiating governance systems for adaptation. Disaster risk management, adjustments in technologies and infrastructure, ecosystem-based approaches, basic public health measures, and livelihood diversification are reducing vulnerability, although efforts to date tend to be isolated.[18]
- In Europe, adaptation policy has been developed across all levels of government, with some adaptation planning integrated into coastal and water management, into environmental protection and land planning, and into disaster risk management.[19]
- In Asia, adaptation is being facilitated in some areas through mainstreaming climate adaptation action into subnational development planning, early warning systems, integrated water resources management, agroforestry, and coastal reforestation of mangroves.[20]
- In Australasia, planning for sea level rise, and in southern Australia for reduced water availability, is becoming adopted widely. Planning for sea level rise has evolved considerably over the past 2 decades and shows a diversity of approaches, although its implementation remains piecemeal.[21]
- In North America, governments are engaging in incremental adaptation assessment and planning, particularly at the municipal level. Some proactive adaptation is occurring to protect longer-term investments in energy and public infrastructure.[22]
- In Central and South America, ecosystem-based adaptation including protected areas, conservation agreements, and community management of natural areas is occurring. Resilient crop varieties, climate forecasts, and integrated water resources management are being adopted within the agricultural sector in some areas.[23]

[15] 8.2-3, 9.3, 11.3, 13.1-3, 22.3, 24.4, 26.8
[16] 12.5, 19.2, 19.6
[17] 4.4, 5.5, 6.4, 8.3, 9.4, 11.7, 14.1, 14.3-4, 15.2-5, 17.2-3, 21.3, 21.5, 22.4, 23.7, 25.4, 26.8-9, 30.6, Boxes 25-1, 25-2, 25-9, and CC-EA
[18] 22.4
[19] 23.7, Boxes 5-1 and 23-3
[20] 24.4-6, 24.9 Box CC-TC
[21] 25.4, 25.10, Table 25-2, Boxes 25-1, 25-2, and 25-9
[22] 26.7-9
[23] 27.3

- In the Arctic, some communities have begun to deploy adaptive co-management strategies and communications infrastructure, combining traditional and scientific knowledge.[24]
- In small islands, which have diverse physical and human attributes, community-based adaptation has been shown to generate larger benefits when delivered in conjunction with other development activities.[25]
- In the ocean, international cooperation and marine spatial planning are starting to facilitate adaptation to climate change, with constraints from challenges of spatial scale and governance issues.[26]

A-3. The Decision-making Context

Climate variability and extremes have long been important in many decision-making contexts. Climate-related risks are now evolving over time due to both climate change and development. This section builds from existing experience with decision making and risk management. It creates a foundation for understanding the report's assessment of future climate-related risks and potential responses.

Responding to climate-related risks involves decision making in a changing world, with continuing uncertainty about the severity and timing of climate-change impacts and with limits to the effectiveness of adaptation (*high confidence*). Iterative risk management is a useful framework for decision making in complex situations characterized by large potential consequences, persistent uncertainties, long timeframes, potential for learning, and multiple climatic and non-climatic influences changing over time. See Figure SPM.3. Assessment of the widest possible range of potential impacts, including low-probability outcomes with large consequences, is central to understanding the benefits and trade-offs of alternative risk management actions. The complexity of adaptation actions across scales and contexts means that monitoring and learning are important components of effective adaptation.[27]

Adaptation and mitigation choices in the near term will affect the risks of climate change throughout the 21st century (*high confidence*). Figure SPM.4 illustrates projected warming under a low-emission mitigation scenario and a high-emission scenario [Representative Concentration Pathways (RCPs) 2.6 and 8.5], along with observed temperature changes. The benefits of adaptation and mitigation occur over different but overlapping timeframes. Projected global temperature increase over the next few decades is similar across emission scenarios (Figure SPM.4B).[28] During this near-term period, risks will evolve as socioeconomic trends interact with the changing climate. Societal

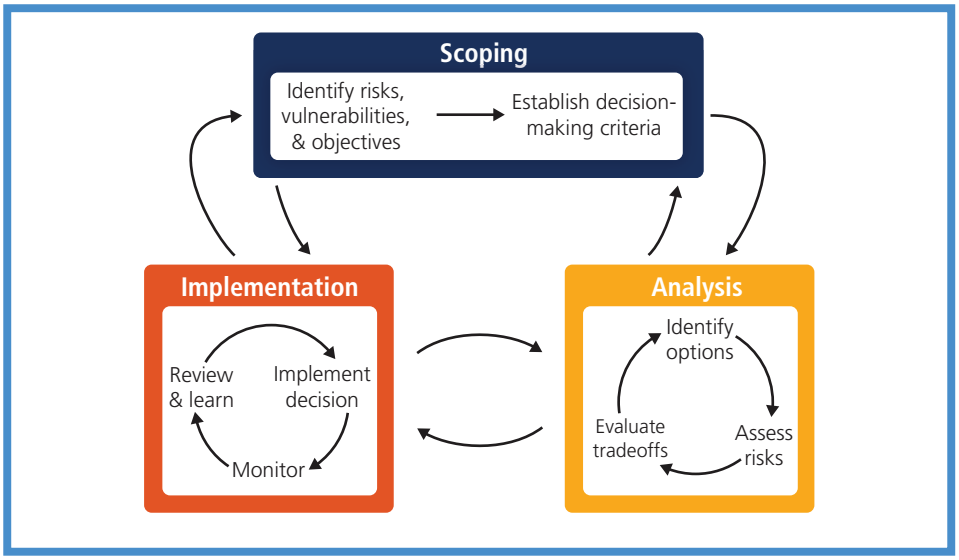


Figure SPM.3 | Climate-change adaptation as an iterative risk management process with multiple feedbacks. People and knowledge shape the process and its outcomes. [Figure 2-1]

[24] 28.2, 28.4
[25] 29.3, 29.6, Table 29-3, Figure 29-1
[26] 30.6
[27] 2.1-4, 3.6, 14.1-3, 15.2-4, 16.2-4, 17.1-3, 17.5, 20.6, 22.4, 25.4, Figure 1-5
[28] WGI AR5 11.3

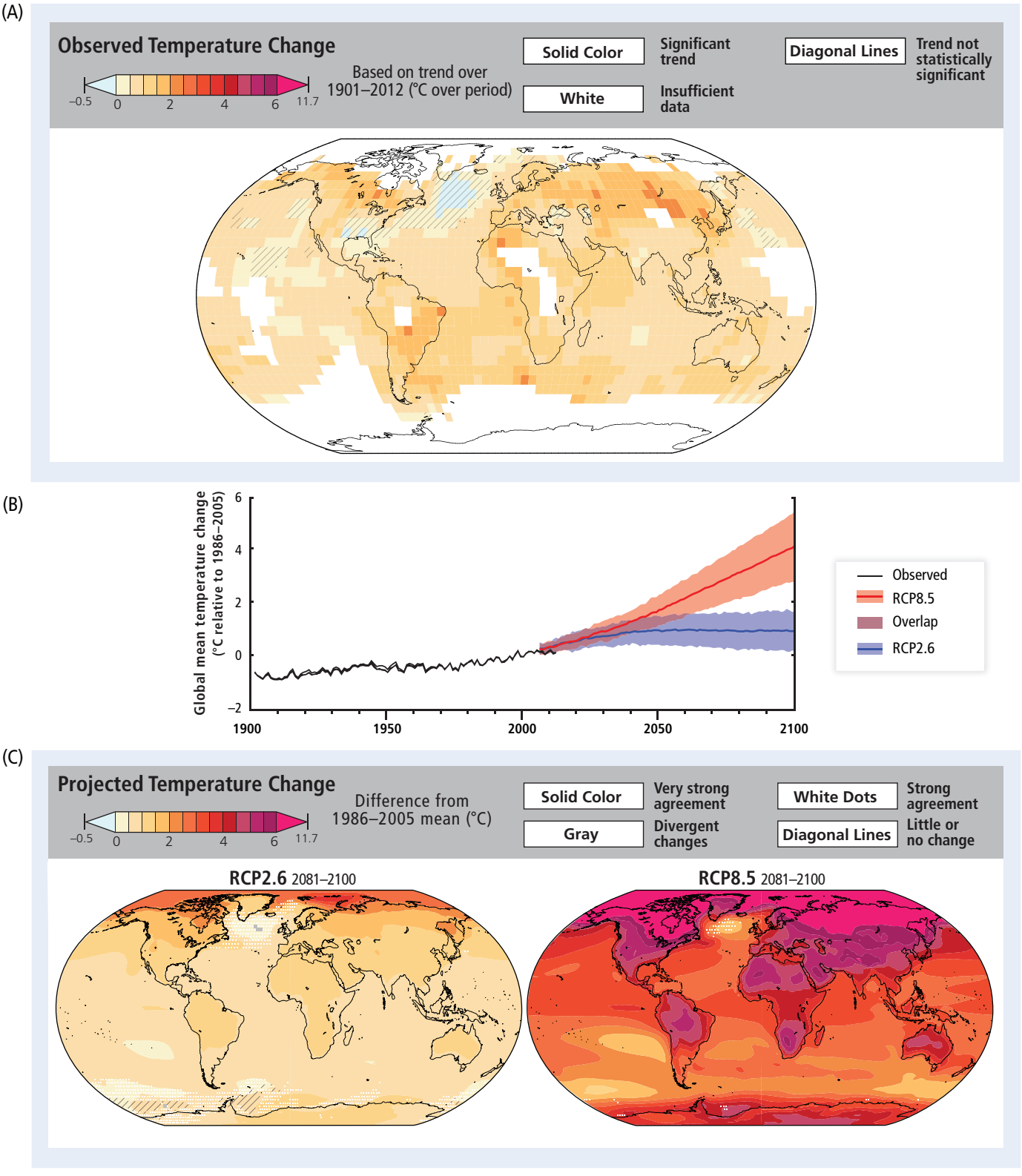


Figure SPM.4 | Observed and projected changes in annual average surface temperature. This figure informs understanding of climate-related risks in the WGII AR5. It illustrates temperature change observed to date and projected warming under continued high emissions and under ambitious mitigation.

Figure SPM.4 Technical Details

(A) Map of observed annual average temperature change from 1901–2012, derived from a linear trend where sufficient data permit a robust estimate; other areas are white. Solid colors indicate areas where trends are significant at the 10% level. Diagonal lines indicate areas where trends are not significant. Observed data (range of grid-point values: –0.53 to 2.50°C over period) are from WGI AR5 Figures SPM.1 and 2.21. (B) Observed and projected future global annual average temperature relative to 1986–2005. Observed warming from 1850–1900 to 1986–2005 is 0.61°C (5–95% confidence interval: 0.55 to 0.67°C). Black lines show temperature estimates from three datasets. Blue and red lines and shading denote the ensemble mean and ±1.64 standard deviation range, based on CMIP5 simulations from 32 models for RCP2.6 and 39 models for RCP8.5. (C) CMIP5 multi-model mean projections of annual average temperature changes for 2081–2100 under RCP2.6 and 8.5, relative to 1986–2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-yr means) and ≥90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where ≥66% of models show change greater than the baseline variability and ≥66% of models agree on sign of change. Gray indicates areas with divergent changes, where ≥66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where <66% of models show change greater than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. Analysis uses model data (range of grid-point values across RCP2.6 and 8.5: 0.06 to 11.71°C) from WGI AR5 Figure SPM.8, with full description of methods in Box CC-RC. See also Annex I of WGI AR5. [Boxes 21-2 and CC-RC; WGI AR5 2.4, Figures SPM.1, SPM.7, and 2.21]

responses, particularly adaptations, will influence near-term outcomes. In the second half of the 21st century and beyond, global temperature increase diverges across emission scenarios (Figure SPM.4B and 4C).[29] For this longer-term period, near-term and longer-term adaptation and mitigation, as well as development pathways, will determine the risks of climate change.[30]

Assessment of risks in the WGII AR5 relies on diverse forms of evidence. Expert judgment is used to integrate evidence into evaluations of risks. Forms of evidence include, for example, empirical observations, experimental results, process-based understanding, statistical approaches, and simulation and descriptive models. Future risks related to climate change vary substantially across plausible alternative development pathways, and the relative importance of development and climate change varies by sector, region, and time period (*high confidence*). Scenarios are useful tools for characterizing possible future socioeconomic pathways, climate change and its risks, and policy implications. Climate-model projections informing evaluations of risks in this report are generally based on the RCPs (Figure SPM.4), as well as the older IPCC *Special Report on Emission Scenarios* (SRES) scenarios.[31]

Uncertainties about future vulnerability, exposure, and responses of interlinked human and natural systems are large (*high confidence*). This motivates exploration of a wide range of socioeconomic futures in assessments of risks. Understanding future vulnerability, exposure, and response capacity of interlinked human and natural systems is challenging due to the number of interacting social, economic, and cultural factors, which have been incompletely considered to date. These factors include wealth and its distribution across society, demographics, migration, access to technology and information, employment patterns, the quality of adaptive responses, societal values, governance structures, and institutions to resolve conflicts. International dimensions such as trade and relations among states are also important for understanding the risks of climate change at regional scales.[32]

B: FUTURE RISKS AND OPPORTUNITIES FOR ADAPTATION

This section presents future risks and more limited potential benefits across sectors and regions, over the next few decades and in the second half of the 21st century and beyond. It examines how they are affected by the magnitude and rate of climate change and by socioeconomic choices. It also assesses opportunities for reducing impacts and managing risks through adaptation and mitigation.

B-1. Key Risks across Sectors and Regions

Key risks are potentially severe impacts relevant to Article 2 of the United Nations Framework Convention on Climate Change, which refers to "dangerous anthropogenic interference with the climate system." Risks are considered key due to high hazard or high vulnerability of societies and systems exposed, or both. Identification of key risks was based on expert judgment using the following specific criteria: large magnitude,

[29] WGI AR5 12.4 and Table SPM.2
[30] 2.5, 21.2-3, 21.5, Box CC-RC
[31] 1.1, 1.3, 2.2-3, 19.6, 20.2, 21.3, 21.5, 26.2, Box CC-RC; WGI AR5 Box SPM.1
[32] 11.3, 12.6, 21.3-5, 25.3-4, 25.11, 26.2

Assessment Box SPM.1 | Human Interference with the Climate System

Human influence on the climate system is clear.[33] Yet determining whether such influence constitutes "dangerous anthropogenic interference" in the words of Article 2 of the UNFCCC involves both risk assessment and value judgments. This report assesses risks across contexts and through time, providing a basis for judgments about the level of climate change at which risks become dangerous.

Five integrative reasons for concern (RFCs) provide a framework for summarizing key risks across sectors and regions. First identified in the IPCC Third Assessment Report, the RFCs illustrate the implications of warming and of adaptation limits for people, economies, and ecosystems. They provide one starting point for evaluating dangerous anthropogenic interference with the climate system. Risks for each RFC, updated based on assessment of the literature and expert judgments, are presented below and in Assessment Box SPM.1 Figure 1. All temperatures below are given as global average temperature change relative to 1986–2005 ("recent").[34]

1) **Unique and threatened systems**: Some unique and threatened systems, including ecosystems and cultures, are already at risk from climate change (*high confidence*). The number of such systems at risk of severe consequences is higher with additional warming of around 1°C. Many species and systems with limited adaptive capacity are subject to very high risks with additional warming of 2°C, particularly Arctic-sea-ice and coral-reef systems.

2) **Extreme weather events**: Climate-change-related risks from extreme events, such as heat waves, extreme precipitation, and coastal flooding, are already moderate (*high confidence*) and high with 1°C additional warming (*medium confidence*). Risks associated with some types of extreme events (e.g., extreme heat) increase further at higher temperatures (*high confidence*).

3) **Distribution of impacts**: Risks are unevenly distributed and are generally greater for disadvantaged people and communities in countries at all levels of development. Risks are already moderate because of regionally differentiated climate-change impacts on crop production in particular (*medium* to *high confidence*). Based on projected decreases in regional crop yields and water availability, risks of unevenly distributed impacts are high for additional warming above 2°C (*medium confidence*).

4) **Global aggregate impacts**: Risks of global aggregate impacts are moderate for additional warming between 1–2°C, reflecting impacts to both Earth's biodiversity and the overall global economy (*medium confidence*). Extensive biodiversity loss with associated loss of ecosystem goods and services results in high risks around 3°C additional warming (*high confidence*). Aggregate economic damages accelerate with increasing temperature (*limited evidence*, *high agreement*), but few quantitative estimates have been completed for additional warming around 3°C or above.

5) **Large-scale singular events**: With increasing warming, some physical systems or ecosystems may be at risk of abrupt and irreversible changes. Risks associated with such tipping points become moderate between 0–1°C additional warming, due to early warning signs that both warm-water coral reef and Arctic ecosystems are already experiencing irreversible regime shifts (*medium confidence*). Risks increase disproportionately as temperature increases between 1–2°C additional warming and become high above 3°C, due to the potential for a large and irreversible sea level rise from ice sheet loss. For sustained warming greater than some threshold,[35] near-complete loss of the Greenland ice sheet would occur over a millennium or more, contributing up to 7 m of global mean sea level rise.

high probability, or irreversibility of impacts; timing of impacts; persistent vulnerability or exposure contributing to risks; or limited potential to reduce risks through adaptation or mitigation. Key risks are integrated into five complementary and overarching reasons for concern (RFCs) in Assessment Box SPM.1.

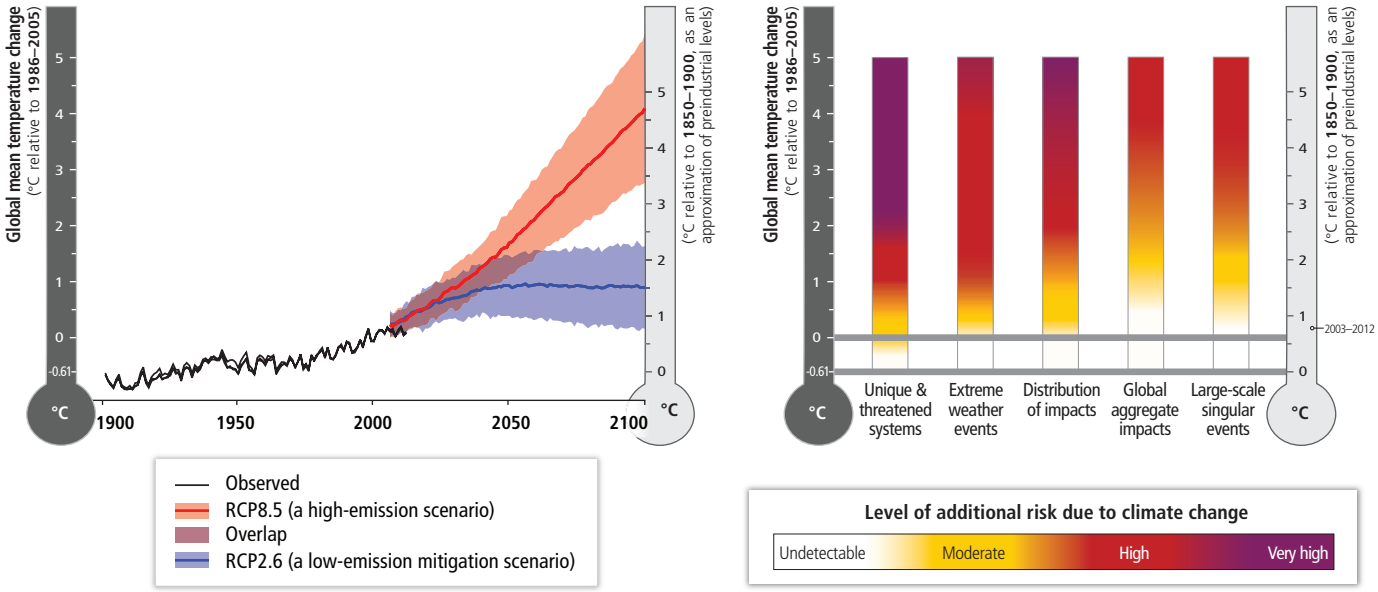
The key risks that follow, all of which are identified with *high confidence*, span sectors and regions. Each of these key risks contributes to one or more RFCs.[36]

[33] WGI AR5 SPM, 2.2, 6.3, 10.3-6, 10.9

[34] 18.6, 19.6; observed warming from 1850–1900 to 1986–2005 is 0.61°C (5–95% confidence interval: 0.55 to 0.67°C). [WGI AR5 2.4]

[35] Current estimates indicate that this threshold is greater than about 1°C (*low confidence*) but less than about 4°C (*medium confidence*) sustained global mean warming above preindustrial levels. [WGI AR5 SPM, 5.8, 13.4-5]

[36] 19.2-4, 19.6, Table 19-4, Boxes 19-2 and CC-KR



Assessment Box SPM.1 Figure 1 | A global perspective on climate-related risks. Risks associated with reasons for concern are shown at right for increasing levels of climate change. The color shading indicates the additional risk due to climate change when a temperature level is reached and then sustained or exceeded. Undetectable risk (white) indicates no associated impacts are detectable and attributable to climate change. Moderate risk (yellow) indicates that associated impacts are both detectable and attributable to climate change with at least *medium confidence*, also accounting for the other specific criteria for key risks. High risk (red) indicates severe and widespread impacts, also accounting for the other specific criteria for key risks. Purple, introduced in this assessment, shows that very high risk is indicated by all specific criteria for key risks. [Figure 19-4] For reference, past and projected global annual average surface temperature is shown at left, as in Figure SPM.4. [Figure RC-1, Box CC-RC; WGI AR5 Figures SPM.1 and SPM.7] Based on the longest global surface temperature dataset available, the observed change between the average of the period 1850–1900 and of the AR5 reference period (1986–2005) is 0.61°C (5–95% confidence interval: 0.55 to 0.67°C) [WGI AR5 SPM, 2.4], which is used here as an approximation of the change in global mean surface temperature since preindustrial times, referred to as the period before 1750. [WGI and WGII AR5 glossaries]

i) Risk of death, injury, ill-health, or disrupted livelihoods in low-lying coastal zones and small island developing states and other small islands, due to storm surges, coastal flooding, and sea level rise.[37] [RFC 1-5]

ii) Risk of severe ill-health and disrupted livelihoods for large urban populations due to inland flooding in some regions.[38] [RFC 2 and 3]

iii) Systemic risks due to extreme weather events leading to breakdown of infrastructure networks and critical services such as electricity, water supply, and health and emergency services.[39] [RFC 2-4]

iv) Risk of mortality and morbidity during periods of extreme heat, particularly for vulnerable urban populations and those working outdoors in urban or rural areas.[40] [RFC 2 and 3]

v) Risk of food insecurity and the breakdown of food systems linked to warming, drought, flooding, and precipitation variability and extremes, particularly for poorer populations in urban and rural settings.[41] [RFC 2-4]

vi) Risk of loss of rural livelihoods and income due to insufficient access to drinking and irrigation water and reduced agricultural productivity, particularly for farmers and pastoralists with minimal capital in semi-arid regions.[42] [RFC 2 and 3]

vii) Risk of loss of marine and coastal ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for coastal livelihoods, especially for fishing communities in the tropics and the Arctic.[43] [RFC 1, 2, and 4]

viii) Risk of loss of terrestrial and inland water ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for livelihoods.[44] [RFC 1, 3, and 4]

Many key risks constitute particular challenges for the least developed countries and vulnerable communities, given their limited ability to cope.

[37] 5.4, 8.2, 13.2, 19.2-4, 19.6-7, 24.4-5, 26.7-8, 29.3, 30.3, Tables 19-4 and 26-1, Figure 26-2, Boxes 25-1, 25-7, and CC-KR
[38] 3.4-5, 8.2, 13.2, 19.6, 25.10, 26.3, 26.8, 27.3, Tables 19-4 and 26-1, Boxes 25-8 and CC-KR
[39] 5.4, 8.1-2, 9.3, 10.2-3, 12.6, 19.6, 23.9, 25.10, 26.7-8, 28.3, Table 19-4, Boxes CC-KR and CC-HS
[40] 8.1-2, 11.3-4, 11.6, 13.2, 19.3, 19.6, 23.5, 24.4, 25.8, 26.6, 26.8, Tables 19-4 and 26-1, Boxes CC-KR and CC-HS
[41] 3.5, 7.4-5, 8.2-3, 9.3, 11.3, 11.6, 13.2, 19.3-4, 19.6, 22.3, 24.4, 25.5, 25.7, 26.5, 26.8, 27.3, 28.2, 28.4, Table 19-4, Box CC-KR
[42] 3.4-5, 9.3, 12.2, 13.2, 19.3, 19.6, 24.4, 25.7, 26.8, Table 19-4, Boxes 25-5 and CC-KR
[43] 5.4, 6.3, 7.4, 9.3, 19.5-6, 22.3, 25.6, 27.3, 28.2-3, 29.3, 30.5-7, Table 19-4, Boxes CC-OA, CC-CR, CC-KR, and CC-HS
[44] 4.3, 9.3, 19.3-6, 22.3, 25.6, 27.3, 28.2-3, Table 19-4, Boxes CC-KR and CC-WE

Increasing magnitudes of warming increase the likelihood of severe, pervasive, and irreversible impacts. Some risks of climate change are considerable at 1 or 2°C above preindustrial levels (as shown in Assessment Box SPM.1). Global climate change risks are high to very high with global mean temperature increase of 4°C or more above preindustrial levels in all reasons for concern (Assessment Box SPM.1), and include severe and widespread impacts on unique and threatened systems, substantial species extinction, large risks to global and regional food security, and the combination of high temperature and humidity compromising normal human activities, including growing food or working outdoors in some areas for parts of the year (*high confidence*). The precise levels of climate change sufficient to trigger tipping points (thresholds for abrupt and irreversible change) remain uncertain, but the risk associated with crossing multiple tipping points in the earth system or in interlinked human and natural systems increases with rising temperature (*medium confidence*).[45]

The overall risks of climate change impacts can be reduced by limiting the rate and magnitude of climate change. Risks are reduced substantially under the assessed scenario with the lowest temperature projections (RCP2.6 – low emissions) compared to the highest temperature projections (RCP8.5 – high emissions), particularly in the second half of the 21st century (*very high confidence*). Reducing climate change can also reduce the scale of adaptation that might be required. Under all assessed scenarios for adaptation and mitigation, some risk from adverse impacts remains (*very high confidence*).[46]

B-2. Sectoral Risks and Potential for Adaptation

Climate change is projected to amplify existing climate-related risks and create new risks for natural and human systems. Some of these risks will be limited to a particular sector or region, and others will have cascading effects. To a lesser extent, climate change is also projected to have some potential benefits.

Freshwater resources

Freshwater-related risks of climate change increase significantly with increasing greenhouse gas concentrations (*robust evidence*, *high agreement*). The fraction of global population experiencing water scarcity and the fraction affected by major river floods increase with the level of warming in the 21st century.[47]

Climate change over the 21st century is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions (*robust evidence*, *high agreement*), intensifying competition for water among sectors (*limited evidence*, *medium agreement*). In presently dry regions, drought frequency will *likely* increase by the end of the 21st century under RCP8.5 (*medium confidence*). In contrast, water resources are projected to increase at high latitudes (*robust evidence*, *high agreement*). Climate change is projected to reduce raw water quality and pose risks to drinking water quality even with conventional treatment, due to interacting factors: increased temperature; increased sediment, nutrient, and pollutant loadings from heavy rainfall; increased concentration of pollutants during droughts; and disruption of treatment facilities during floods (*medium evidence*, *high agreement*). Adaptive water management techniques, including scenario planning, learning-based approaches, and flexible and low-regret solutions, can help create resilience to uncertain hydrological changes and impacts due to climate change (*limited evidence*, *high agreement*).[48]

Terrestrial and freshwater ecosystems

A large fraction of both terrestrial and freshwater species faces increased extinction risk under projected climate change during and beyond the 21st century, especially as climate change interacts with other stressors, such as habitat modification, over-

[45] 4.2-3, 11.8, 19.5, 19.7, 26.5, Box CC-HS
[46] 3.4-5, 16.6, 17.2, 19.7, 20.3, 25.10, Tables 3-2, 8-3, and 8-6, Boxes 16-3 and 25-1
[47] 3.4-5, 26.3, Table 3-2, Box 25-8

exploitation, pollution, and invasive species (*high confidence*). Extinction risk is increased under all RCP scenarios, with risk increasing with both magnitude and rate of climate change. Many species will be unable to track suitable climates under mid- and high-range rates of climate change (i.e., RCP4.5, 6.0, and 8.5) during the 21st century (*medium confidence*). Lower rates of change (i.e., RCP2.6) will pose fewer problems. See Figure SPM.5. Some species will adapt to new climates. Those that cannot adapt sufficiently fast will decrease in abundance or go extinct in part or all of their ranges. Management actions, such as maintenance of genetic diversity, assisted species migration and dispersal, manipulation of disturbance regimes (e.g., fires, floods), and reduction of other stressors, can reduce, but not eliminate, risks of impacts to terrestrial and freshwater ecosystems due to climate change, as well as increase the inherent capacity of ecosystems and their species to adapt to a changing climate (*high confidence*).[49]

Within this century, magnitudes and rates of climate change associated with medium- to high-emission scenarios (RCP4.5, 6.0, and 8.5) pose high risk of abrupt and irreversible regional-scale change in the composition, structure, and function of terrestrial and freshwater ecosystems, including wetlands (*medium confidence*). Examples that could lead to substantial impact on climate are the boreal-tundra Arctic system (*medium confidence*) and the Amazon forest (*low confidence*). Carbon stored in the terrestrial biosphere (e.g., in peatlands, permafrost, and forests) is susceptible to loss to the atmosphere as a result of climate change, deforestation, and ecosystem degradation (*high confidence*). Increased tree mortality and associated forest dieback is projected to occur in many regions over the 21st century, due to increased temperatures and drought (*medium confidence*). Forest dieback poses risks for carbon storage, biodiversity, wood production, water quality, amenity, and economic activity.[50]

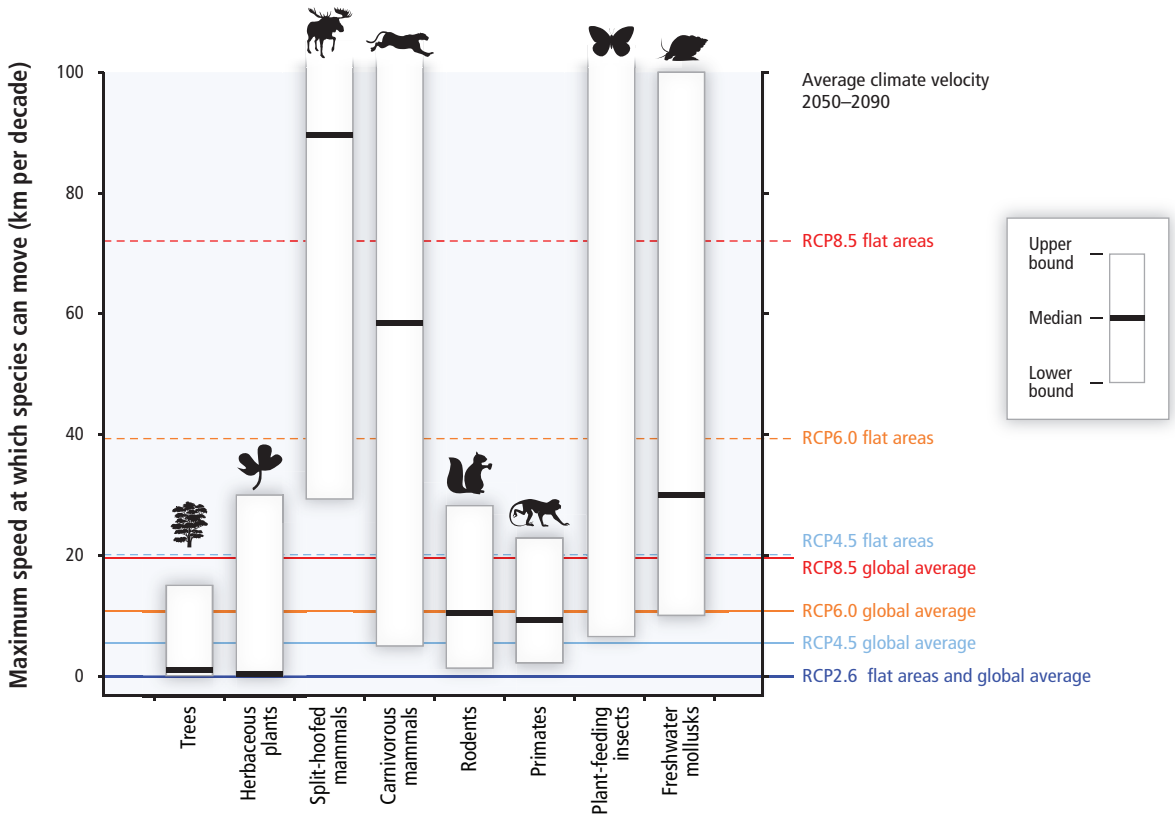


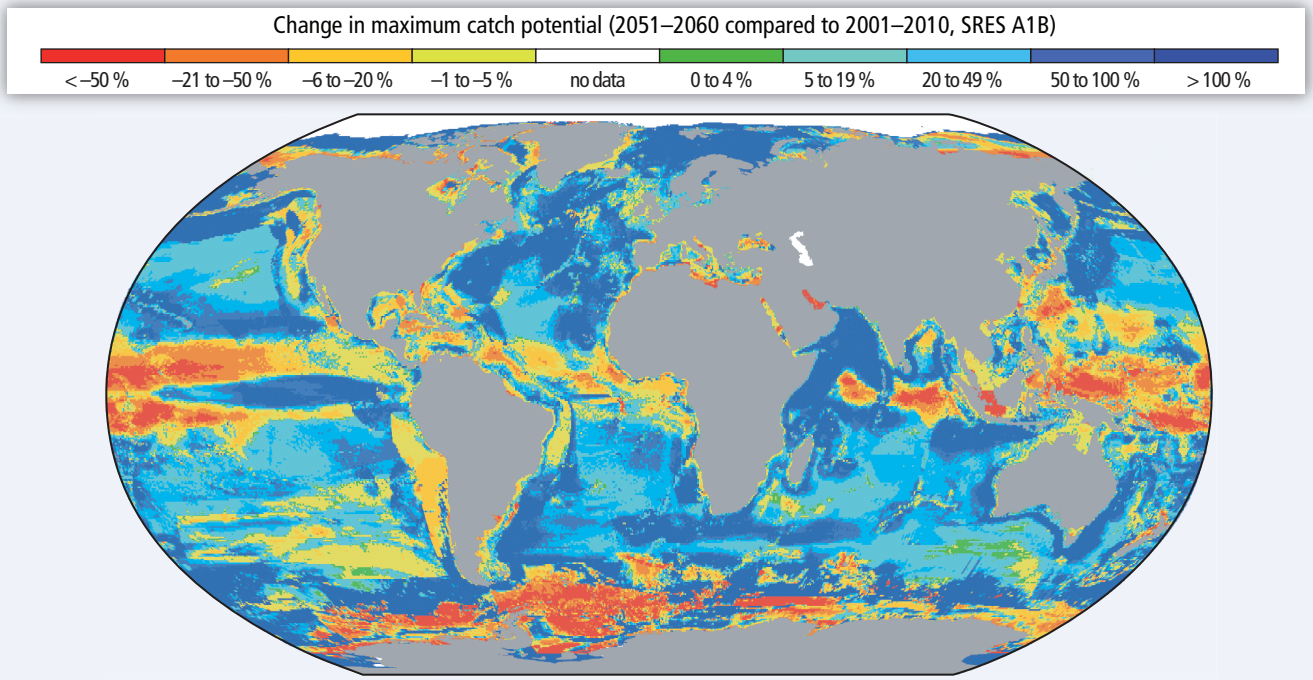
Figure SPM.5 | Maximum speeds at which species can move across landscapes (based on observations and models; vertical axis on left), compared with speeds at which temperatures are projected to move across landscapes (climate velocities for temperature; vertical axis on right). Human interventions, such as transport or habitat fragmentation, can greatly increase or decrease speeds of movement. White boxes with black bars indicate ranges and medians of maximum movement speeds for trees, plants, mammals, plant-feeding insects (median not estimated), and freshwater mollusks. For RCP2.6, 4.5, 6.0, and 8.5 for 2050–2090, horizontal lines show climate velocity for the global-land-area average and for large flat regions. Species with maximum speeds below each line are expected to be unable to track warming in the absence of human intervention. [Figure 4-5]

[48] 3.2, 3.4-6, 22.3, 23.9, 25.5, 26.3, Table 3-2, Table 23-3, Boxes 25-2, CC-RF, and CC-WE; WGI AR5 12.4

[49] 4.3-4, 25.6, 26.4, Box CC-RF

[50] 4.2-3, Figure 4-8, Boxes 4-2, 4-3, and 4-4

(A)


Change in maximum catch potential (2051–2060 compared to 2001–2010, SRES A1B)
< –50 %
–21 to –50 %
–6 to –20 %
–1 to –5 %
no data
0 to 4 %
5 to 19 %
20 to 49 %
50 to 100 %
> 100 %

(B)

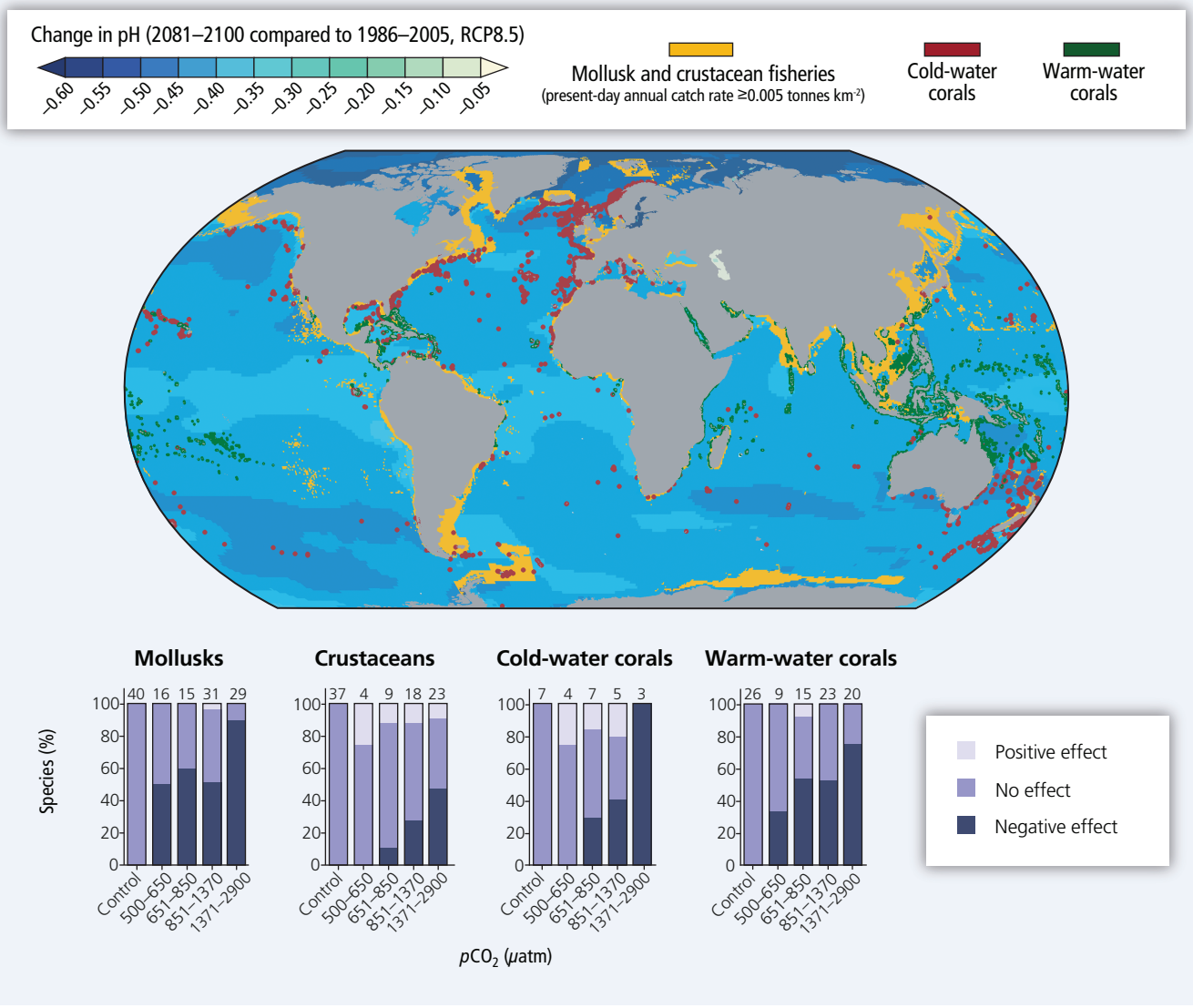

Change in pH (2081–2100 compared to 1986–2005, RCP8.5)
–0.60
–0.55
–0.50
–0.45
–0.40
–0.35
–0.30
–0.25
–0.20
–0.15
–0.10
–0.05
Mollusk and crustacean fisheries
(present-day annual catch rate ≥0.005 tonnes km-2)
Cold-water corals
Warm-water corals
Mollusks
Crustaceans
Cold-water corals
Warm-water corals
Species (%)
40 16 15 31 29
37 4 9 18 23
7 4 7 5 3
26 9 15 23 20
Control
500–650
651–850
851–1370
1371–2900
pCO2 (µatm)
Positive effect
No effect
Negative effect

Figure SPM.6 | Climate change risks for fisheries. (A) Projected global redistribution of maximum catch potential of ~1000 exploited fish and invertebrate species. Projections compare the 10-year averages 2001–2010 and 2051–2060 using SRES A1B, without analysis of potential impacts of overfishing or ocean acidification. (B) Marine mollusk and crustacean fisheries (present-day estimated annual catch rates ≥0.005 tonnes km^{-2}) and known locations of cold- and warm-water corals, depicted on a global map showing the projected distribution of ocean acidification under RCP8.5 (pH change from 1986–2005 to 2081–2100). [WGI AR5 Figure SPM.8] The bottom panel compares sensitivity to ocean acidification across mollusks, crustaceans, and corals, vulnerable animal phyla with socioeconomic relevance (e.g., for coastal protection and fisheries). The number of species analyzed across studies is given for each category of elevated CO_2. For 2100, RCP scenarios falling within each CO_2 partial pressure (pCO_2) category are as follows: RCP4.5 for 500–650 μatm (approximately equivalent to ppm in the atmosphere), RCP6.0 for 651–850 μatm, and RCP8.5 for 851–1370 μatm. By 2150, RCP8.5 falls within the 1371–2900 μatm category. The control category corresponds to 380 μatm. [6.1, 6.3, 30.5, Figures 6-10 and 6-14; WGI AR5 Box SPM.1]

Coastal systems and low-lying areas

Due to sea level rise projected throughout the 21st century and beyond, coastal systems and low-lying areas will increasingly experience adverse impacts such as submergence, coastal flooding, and coastal erosion (*very high confidence*). The population and assets projected to be exposed to coastal risks as well as human pressures on coastal ecosystems will increase significantly in the coming decades due to population growth, economic development, and urbanization (*high confidence*). The relative costs of coastal adaptation vary strongly among and within regions and countries for the 21st century. Some low-lying developing countries and small island states are expected to face very high impacts that, in some cases, could have associated damage and adaptation costs of several percentage points of GDP.[51]

Marine systems

Due to projected climate change by the mid 21st century and beyond, global marine-species redistribution and marine-biodiversity reduction in sensitive regions will challenge the sustained provision of fisheries productivity and other ecosystem services (*high confidence*). Spatial shifts of marine species due to projected warming will cause high-latitude invasions and high local-extinction rates in the tropics and semi-enclosed seas (*medium confidence*). Species richness and fisheries catch potential are projected to increase, on average, at mid and high latitudes (*high confidence*) and decrease at tropical latitudes (*medium confidence*). See Figure SPM.6A. The progressive expansion of oxygen minimum zones and anoxic "dead zones" is projected to further constrain fish habitat. Open-ocean net primary production is projected to redistribute and, by 2100, fall globally under all RCP scenarios. Climate change adds to the threats of over-fishing and other non-climatic stressors, thus complicating marine management regimes (*high confidence*).[52]

For medium- to high-emission scenarios (RCP4.5, 6.0, and 8.5), ocean acidification poses substantial risks to marine ecosystems, especially polar ecosystems and coral reefs, associated with impacts on the physiology, behavior, and population dynamics of individual species from phytoplankton to animals (*medium* to *high confidence*). Highly calcified mollusks, echinoderms, and reef-building corals are more sensitive than crustaceans (*high confidence*) and fishes (*low confidence*), with potentially detrimental consequences for fisheries and livelihoods. See Figure SPM.6B. Ocean acidification acts together with other global changes (e.g., warming, decreasing oxygen levels) and with local changes (e.g., pollution, eutrophication) (*high confidence*). Simultaneous drivers, such as warming and ocean acidification, can lead to interactive, complex, and amplified impacts for species and ecosystems.[53]

Food security and food production systems

For the major crops (wheat, rice, and maize) in tropical and temperate regions, climate change without adaptation is projected to negatively impact production for local temperature increases of 2°C or more above late-20th-century levels, although individual locations may benefit (*medium confidence*). Projected impacts vary across crops and regions and adaptation scenarios, with about 10% of projections for the period 2030–2049 showing yield gains of more than 10%, and about 10% of projections showing yield losses of more than

[51] 5.3-5, 8.2, 22.3, 24.4, 25.6, 26.3, 26.8, Table 26-1, Box 25-1
[52] 6.3-5, 7.4, 25.6, 28.3, 30.6-7, Boxes CC-MB and CC-PP
[53] 5.4, 6.3-5, 22.3, 25.6, 28.3, 30.5, Boxes CC-CR, CC-OA, and TS.7

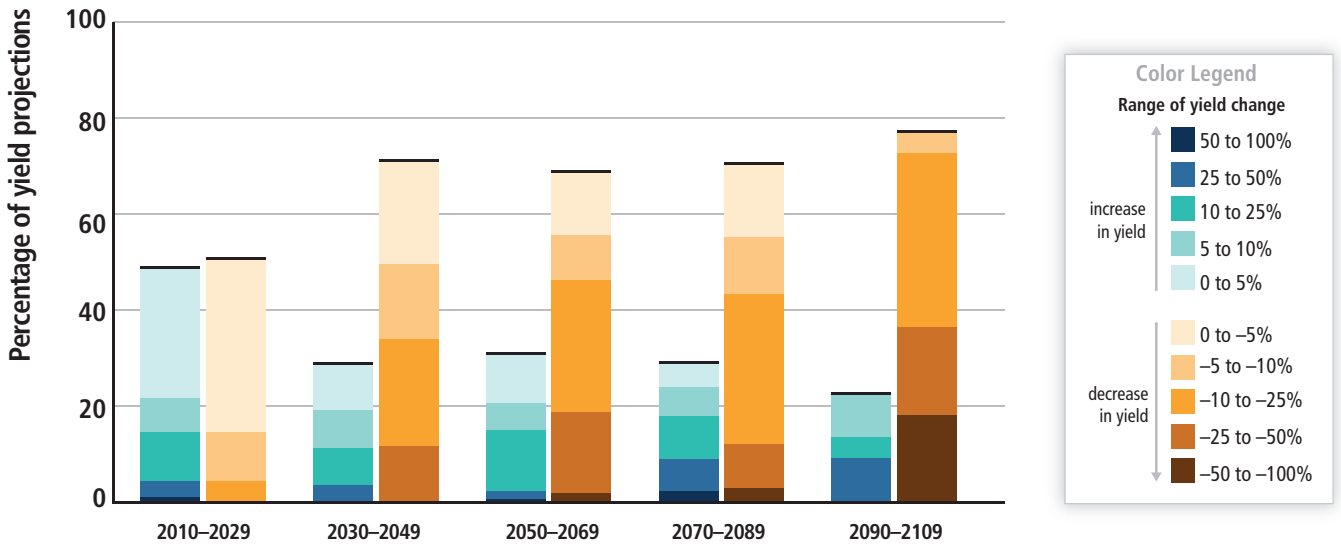


Figure SPM.7 | Summary of projected changes in crop yields, due to climate change over the 21st century. The figure includes projections for different emission scenarios, for tropical and temperate regions, and for adaptation and no-adaptation cases combined. Relatively few studies have considered impacts on cropping systems for scenarios where global mean temperatures increase by 4°C or more. For five timeframes in the near term and long term, data (n=1090) are plotted in the 20-year period on the horizontal axis that includes the midpoint of each future projection period. Changes in crop yields are relative to late-20th-century levels. Data for each timeframe sum to 100%. [Figure 7-5]

25%, compared to the late 20th century. After 2050 the risk of more severe yield impacts increases and depends on the level of warming. See Figure SPM.7. Climate change is projected to progressively increase inter-annual variability of crop yields in many regions. These projected impacts will occur in the context of rapidly rising crop demand.[54]

All aspects of food security are potentially affected by climate change, including food access, utilization, and price stability (*high confidence*). Redistribution of marine fisheries catch potential towards higher latitudes poses risk of reduced supplies, income, and employment in tropical countries, with potential implications for food security (*medium confidence*). Global temperature increases of ~4°C or more above late-20th-century levels, combined with increasing food demand, would pose large risks to food security globally and regionally (*high confidence*). Risks to food security are generally greater in low-latitude areas.[55]

Urban areas

Many global risks of climate change are concentrated in urban areas (*medium confidence*). Steps that build resilience and enable sustainable development can accelerate successful climate-change adaptation globally. Heat stress, extreme precipitation, inland and coastal flooding, landslides, air pollution, drought, and water scarcity pose risks in urban areas for people, assets, economies, and ecosystems (*very high confidence*). Risks are amplified for those lacking essential infrastructure and services or living in poor-quality housing and exposed areas. Reducing basic service deficits, improving housing, and building resilient infrastructure systems could significantly reduce vulnerability and exposure in urban areas. Urban adaptation benefits from effective multi-level urban risk governance, alignment of policies and incentives, strengthened local government and community adaptation capacity, synergies with the private sector, and appropriate financing and institutional development (*medium confidence*). Increased capacity, voice, and influence of low-income groups and vulnerable communities and their partnerships with local governments also benefit adaptation.[56]

[54] 7.4-5, 22.3, 24.4, 25.7, 26.5, Table 7-2, Figures 7-4, 7-5, 7-6, 7-7, and 7-8
[55] 6.3-5, 7.4-5, 9.3, 22.3, 24.4, 25.7, 26.5, Table 7-3, Figures 7-1, 7-4, and 7-7, Box 7-1
[56] 3.5, 8.2-4, 22.3, 24.4-5, 26.8, Table 8-2, Boxes 25-9 and CC-HS

Rural areas

Major future rural impacts are expected in the near term and beyond through impacts on water availability and supply, food security, and agricultural incomes, including shifts in production areas of food and non-food crops across the world (*high confidence*). These impacts are expected to disproportionately affect the welfare of the poor in rural areas, such as female-headed households and those with limited access to land, modern agricultural inputs, infrastructure, and education. Further adaptations for agriculture, water, forestry, and biodiversity can occur through policies taking account of rural decision-making contexts. Trade reform and investment can improve market access for small-scale farms (*medium confidence*).[57]

Key economic sectors and services

For most economic sectors, the impacts of drivers such as changes in population, age structure, income, technology, relative prices, lifestyle, regulation, and governance are projected to be large relative to the impacts of climate change (*medium evidence*, *high agreement*). Climate change is projected to reduce energy demand for heating and increase energy demand for cooling in the residential and commercial sectors (*robust evidence*, *high agreement*). Climate change is projected to affect energy sources and technologies differently, depending on resources (e.g., water flow, wind, insolation), technological processes (e.g., cooling), or locations (e.g., coastal regions, floodplains) involved. More severe and/or frequent extreme weather events and/or hazard types are projected to increase losses and loss variability in various regions and challenge insurance systems to offer affordable coverage while raising more risk-based capital, particularly in developing countries. Large-scale public-private risk reduction initiatives and economic diversification are examples of adaptation actions.[58]

Global economic impacts from climate change are difficult to estimate. Economic impact estimates completed over the past 20 years vary in their coverage of subsets of economic sectors and depend on a large number of assumptions, many of which are disputable, and many estimates do not account for catastrophic changes, tipping points, and many other factors.[59] With these recognized limitations, the incomplete estimates of global annual economic losses for additional temperature increases of ~2°C are between 0.2 and 2.0% of income (±1 standard deviation around the mean) (*medium evidence*, *medium agreement*). Losses are *more likely than not* to be greater, rather than smaller, than this range (*limited evidence*, *high agreement*). Additionally, there are large differences between and within countries. Losses accelerate with greater warming (*limited evidence*, *high agreement*), but few quantitative estimates have been completed for additional warming around 3°C or above. Estimates of the incremental economic impact of emitting carbon dioxide lie between a few dollars and several hundreds of dollars per tonne of carbon[60] (*robust evidence*, *medium agreement*). Estimates vary strongly with the assumed damage function and discount rate.[61]

Human health

Until mid-century, projected climate change will impact human health mainly by exacerbating health problems that already exist (*very high confidence*). Throughout the 21st century, climate change is expected to lead to increases in ill-health in many regions and especially in developing countries with low income, as compared to a baseline without climate change (*high confidence*). Examples include greater likelihood of injury, disease, and death due to more intense heat waves and fires (*very high confidence*); increased likelihood of under-nutrition resulting from diminished food production in poor regions (*high confidence*); risks from lost work capacity and reduced labor productivity in vulnerable populations; and increased risks from food- and water-borne diseases (*very high confidence*) and

[57] 9.3, 25.9, 26.8, 28.2, 28.4, Box 25-5

[58] 3.5, 10.2, 10.7, 10.10, 17.4-5, 25.7, 26.7-9, Box 25-7

[59] Disaster loss estimates are lower-bound estimates because many impacts, such as loss of human lives, cultural heritage, and ecosystem services, are difficult to value and monetize, and thus they are poorly reflected in estimates of losses. Impacts on the informal or undocumented economy as well as indirect economic effects can be very important in some areas and sectors, but are generally not counted in reported estimates of losses. [SREX 4.5]

[60] 1 tonne of carbon = 3.667 tonne of CO_2

[61] 10.9

vector-borne diseases (*medium confidence*). Positive effects are expected to include modest reductions in cold-related mortality and morbidity in some areas due to fewer cold extremes (*low confidence*), geographical shifts in food production (*medium confidence*), and reduced capacity of vectors to transmit some diseases. But globally over the 21st century, the magnitude and severity of negative impacts are projected to increasingly outweigh positive impacts (*high confidence*). The most effective vulnerability reduction measures for health in the near term are programs that implement and improve basic public health measures such as provision of clean water and sanitation, secure essential health care including vaccination and child health services, increase capacity for disaster preparedness and response, and alleviate poverty (*very high confidence*). By 2100 for the high-emission scenario RCP8.5, the combination of high temperature and humidity in some areas for parts of the year is projected to compromise normal human activities, including growing food or working outdoors (*high confidence*).[62]

Human security

Climate change over the 21st century is projected to increase displacement of people (*medium evidence*, *high agreement*). Displacement risk increases when populations that lack the resources for planned migration experience higher exposure to extreme weather events, in both rural and urban areas, particularly in developing countries with low income. Expanding opportunities for mobility can reduce vulnerability for such populations. Changes in migration patterns can be responses to both extreme weather events and longer-term climate variability and change, and migration can also be an effective adaptation strategy. There is *low confidence* in quantitative projections of changes in mobility, due to its complex, multi-causal nature.[63]

Climate change can indirectly increase risks of violent conflicts in the form of civil war and inter-group violence by amplifying well-documented drivers of these conflicts such as poverty and economic shocks (*medium confidence*). Multiple lines of evidence relate climate variability to these forms of conflict.[64]

The impacts of climate change on the critical infrastructure and territorial integrity of many states are expected to influence national security policies (*medium evidence*, *medium agreement*). For example, land inundation due to sea level rise poses risks to the territorial integrity of small island states and states with extensive coastlines. Some transboundary impacts of climate change, such as changes in sea ice, shared water resources, and pelagic fish stocks, have the potential to increase rivalry among states, but robust national and intergovernmental institutions can enhance cooperation and manage many of these rivalries.[65]

Livelihoods and poverty

Throughout the 21st century, climate-change impacts are projected to slow down economic growth, make poverty reduction more difficult, further erode food security, and prolong existing and create new poverty traps, the latter particularly in urban areas and emerging hotspots of hunger (*medium confidence*). Climate-change impacts are expected to exacerbate poverty in most developing countries and create new poverty pockets in countries with increasing inequality, in both developed and developing countries. In urban and rural areas, wage-labor-dependent poor households that are net buyers of food are expected to be particularly affected due to food price increases, including in regions with high food insecurity and high inequality (particularly in Africa), although the agricultural self-employed could benefit. Insurance programs, social protection measures, and disaster risk management may enhance long-term livelihood resilience among poor and marginalized people, if policies address poverty and multidimensional inequalities.[66]

B-3. Regional Key Risks and Potential for Adaptation

Risks will vary through time across regions and populations, dependent on myriad factors including the extent of adaptation and mitigation. A selection of key regional risks identified with *medium* to *high confidence* is presented in Assessment Box SPM.2. For extended summary of regional risks and potential benefits, see Technical Summary Section B-3 and WGII AR5 Part B: Regional Aspects.

Assessment Box SPM.2 | Regional Key Risks

The accompanying Assessment Box SPM.2 Table 1 highlights several representative key risks for each region. Key risks have been identified based on assessment of the relevant scientific, technical, and socioeconomic literature detailed in supporting chapter sections. Identification of key risks was based on expert judgment using the following specific criteria: large magnitude, high probability, or irreversibility of impacts; timing of impacts; persistent vulnerability or exposure contributing to risks; or limited potential to reduce risks through adaptation or mitigation.

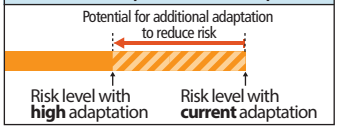
For each key risk, risk levels were assessed for three timeframes. For the present, risk levels were estimated for current adaptation and a hypothetical highly adapted state, identifying where current adaptation deficits exist. For two future timeframes, risk levels were estimated for a continuation of current adaptation and for a highly adapted state, representing the potential for and limits to adaptation. The risk levels integrate probability and consequence over the widest possible range of potential outcomes, based on available literature. These potential outcomes result from the interaction of climate-related hazards, vulnerability, and exposure. Each risk level reflects total risk from climatic and non-climatic factors. Key risks and risk levels vary across regions and over time, given differing socioeconomic development pathways, vulnerability and exposure to hazards, adaptive capacity, and risk perceptions. Risk levels are not necessarily comparable, especially across regions, because the assessment considers potential impacts and adaptation in different physical, biological, and human systems across diverse contexts. This assessment of risks acknowledges the importance of differences in values and objectives in interpretation of the assessed risk levels.

Assessment Box SPM.2 Table 1 | Key regional risks from climate change and the potential for reducing risks through adaptation and mitigation. Each key risk is characterized as very low to very high for three timeframes: the present, near term (here, assessed over 2030–2040), and longer term (here, assessed over 2080–2100). In the near term, projected levels of global mean temperature increase do not diverge substantially for different emission scenarios. For the longer term, risk levels are presented for two scenarios of global mean temperature increase (2°C and 4°C above preindustrial levels). These scenarios illustrate the potential for mitigation and adaptation to reduce the risks related to climate change. Climate-related drivers of impacts are indicated by icons.

Climate-related drivers of impacts

Warming trend; Extreme temperature; Drying trend; Extreme precipitation; Precipitation; Snow cover; Damaging cyclone; Sea level; Ocean acidification; Carbon dioxide fertilization

Level of risk & potential for adaptation



Africa

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Compounded stress on water resources facing significant strain from overexploitation and degradation at present and increased demand in the future, with drought stress exacerbated in drought-prone regions of Africa (*high confidence*) [22.3-4]	• Reducing non-climate stressors on water resources • Strengthening institutional capacities for demand management, groundwater assessment, integrated water-wastewater planning, and integrated land and water governance • Sustainable urban development		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high
Reduced crop productivity associated with heat and drought stress, with strong adverse effects on regional, national, and household livelihood and food security, also given increased pest and disease damage and flood impacts on food system infrastructure (*high confidence*) [22.3-4]	• Technological adaptation responses (e.g., stress-tolerant crop varieties, irrigation, enhanced observation systems) • Enhancing smallholder access to credit and other critical production resources; Diversifying livelihoods • Strengthening institutions at local, national, and regional levels to support agriculture (including early warning systems) and gender-oriented policy • Agronomic adaptation responses (e.g., agroforestry, conservation agriculture)		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high
Changes in the incidence and geographic range of vector- and water-borne diseases due to changes in the mean and variability of temperature and precipitation, particularly along the edges of their distribution (*medium confidence*) [22.3]	• Achieving development goals, particularly improved access to safe water and improved sanitation, and enhancement of public health functions such as surveillance • Vulnerability mapping and early warning systems • Coordination across sectors • Sustainable urban development		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high

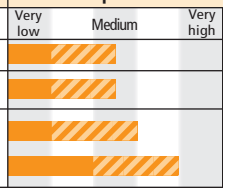
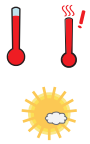
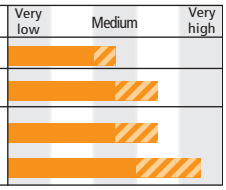
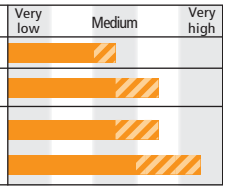
[62] 8.2, 11.3-8, 19.3, 22.3, 25.8, 26.6, Figure 25-5, Box CC-HS
[63] 9.3, 12.4, 19.4, 22.3, 25.9
[64] 12.5, 13.2, 19.4
[65] 12.5-6, 23.9, 25.9
[66] 8.1, 8.3-4, 9.3, 10.9, 13.2-4, 22.3, 26.8

Continued next page →

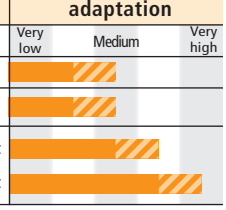
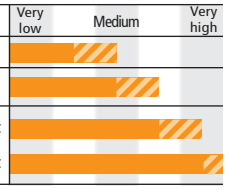
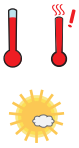
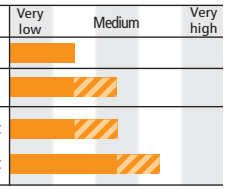
Assessment Box SPM.2 Table 1 (continued)

Continued next page →

Europe

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Increased economic losses and people affected by flooding in river basins and coasts, driven by increasing urbanization, increasing sea levels, coastal erosion, and peak river discharges (*high confidence*) [23.2-3, 23.7]	Adaptation can prevent most of the projected damages (*high confidence*). • Significant experience in hard flood-protection technologies and increasing experience with restoring wetlands • High costs for increasing flood protection • Potential barriers to implementation: demand for land in Europe and environmental and landscape concerns		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Increased water restrictions. Significant reduction in water availability from river abstraction and from groundwater resources, combined with increased water demand (e.g., for irrigation, energy and industry, domestic use) and with reduced water drainage and runoff as a result of increased evaporative demand, particularly in southern Europe (*high confidence*) [23.4, 23.7]	• Proven adaptation potential from adoption of more water-efficient technologies and of water-saving strategies (e.g., for irrigation, crop species, land cover, industries, domestic use) • Implementation of best practices and governance instruments in river basin management plans and integrated water management		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Increased economic losses and people affected by extreme heat events: impacts on health and well-being, labor productivity, crop production, air quality, and increasing risk of wildfires in southern Europe and in Russian boreal region (*medium confidence*) [23.3-7, Table 23-1]	• Implementation of warning systems • Adaptation of dwellings and workplaces and of transport and energy infrastructure • Reductions in emissions to improve air quality • Improved wildfire management • Development of insurance products against weather-related yield variations		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	

Asia

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Increased riverine, coastal, and urban flooding leading to widespread damage to infrastructure, livelihoods, and settlements in Asia (*medium confidence*) [24.4]	• Exposure reduction via structural and non-structural measures, effective land-use planning, and selective relocation • Reduction in the vulnerability of lifeline infrastructure and services (e.g., water, energy, waste management, food, biomass, mobility, local ecosystems, telecommunications) • Construction of monitoring and early warning systems; Measures to identify exposed areas, assist vulnerable areas and households, and diversify livelihoods • Economic diversification		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Increased risk of heat-related mortality (*high confidence*) [24.4]	• Heat health warning systems • Urban planning to reduce heat islands; Improvement of the built environment; Development of sustainable cities • New work practices to avoid heat stress among outdoor workers		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Increased risk of drought-related water and food shortage causing malnutrition (*high confidence*) [24.4]	• Disaster preparedness including early-warning systems and local coping strategies • Adaptive/integrated water resource management • Water infrastructure and reservoir development • Diversification of water sources including water re-use • More efficient use of water (e.g., improved agricultural practices, irrigation management, and resilient agriculture)		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	

Assessment Box SPM.2 Table 1 (continued)

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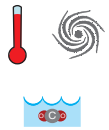
Australasia

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Significant change in community composition and structure of coral reef systems in Australia (*high confidence*) [25.6, 30.5, Boxes CC-CR and CC-OA]	• Ability of corals to adapt naturally appears limited and insufficient to offset the detrimental effects of rising temperatures and acidification. • Other options are mostly limited to reducing other stresses (water quality, tourism, fishing) and early warning systems; direct interventions such as assisted colonization and shading have been proposed but remain untested at scale.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high
Increased frequency and intensity of flood damage to infrastructure and settlements in Australia and New Zealand (*high confidence*) [Table 25-1, Boxes 25-8 and 25-9]	• Significant adaptation deficit in some regions to current flood risk. • Effective adaptation includes land-use controls and relocation as well as protection and accommodation of increased risk to ensure flexibility.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high
Increasing risks to coastal infrastructure and low-lying ecosystems in Australia and New Zealand, with widespread damage towards the upper end of projected sea-level-rise ranges (*high confidence*) [25.6, 25.10, Box 25-1]	• Adaptation deficit in some locations to current coastal erosion and flood risk. Successive building and protection cycles constrain flexible responses. • Effective adaptation includes land-use controls and ultimately relocation as well as protection and accommodation.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high

North America

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Wildfire-induced loss of ecosystem integrity, property loss, human morbidity, and mortality as a result of increased drying trend and temperature trend (*high confidence*) [26.4, 26.8, Box 26-2]	• Some ecosystems are more fire-adapted than others. Forest managers and municipal planners are increasingly incorporating fire protection measures (e.g., prescribed burning, introduction of resilient vegetation). Institutional capacity to support ecosystem adaptation is limited. • Adaptation of human settlements is constrained by rapid private property development in high-risk areas and by limited household-level adaptive capacity. • Agroforestry can be an effective strategy for reduction of slash and burn practices in Mexico.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high
Heat-related human mortality (*high confidence*) [26.6, 26.8]	• Residential air conditioning (A/C) can effectively reduce risk. However, availability and usage of A/C is highly variable and is subject to complete loss during power failures. Vulnerable populations include athletes and outdoor workers for whom A/C is not available. • Community- and household-scale adaptations have the potential to reduce exposure to heat extremes via family support, early heat warning systems, cooling centers, greening, and high-albedo surfaces.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high
Urban floods in riverine and coastal areas, inducing property and infrastructure damage; supply chain, ecosystem, and social system disruption; public health impacts; and water quality impairment, due to sea level rise, extreme precipitation, and cyclones (*high confidence*) [26.2-4, 26.8]	• Implementing management of urban drainage is expensive and disruptive to urban areas. • Low-regret strategies with co-benefits include less impervious surfaces leading to more groundwater recharge, green infrastructure, and rooftop gardens. • Sea level rise increases water elevations in coastal outfalls, which impedes drainage. In many cases, older rainfall design standards are being used that need to be updated to reflect current climate conditions. • Conservation of wetlands, including mangroves, and land-use planning strategies can reduce the intensity of flood events.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high

Assessment Box SPM.2 Table 1 (continued)

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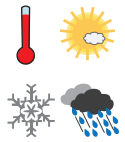
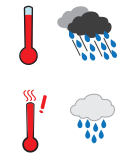
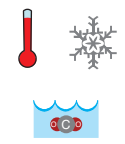
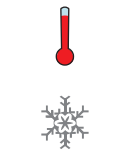
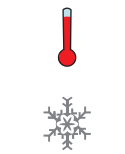
Central and South America

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Water availability in semi-arid and glacier-melt-dependent regions and Central America; flooding and landslides in urban and rural areas due to extreme precipitation (*high confidence*) [27.3]	• Integrated water resource management • Urban and rural flood management (including infrastructure), early warning systems, better weather and runoff forecasts, and infectious disease control		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Decreased food production and food quality (*medium confidence*) [27.3]	• Development of new crop varieties more adapted to climate change (temperature and drought) • Offsetting of human and animal health impacts of reduced food quality • Offsetting of economic impacts of land-use change • Strengthening traditional indigenous knowledge systems and practices		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Spread of vector-borne diseases in altitude and latitude (*high confidence*) [27.3]	• Development of early warning systems for disease control and mitigation based on climatic and other relevant inputs. Many factors augment vulnerability. • Establishing programs to extend basic public health services		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high not available not available

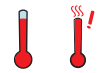
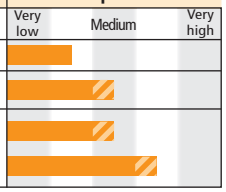
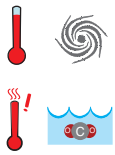
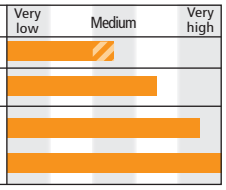
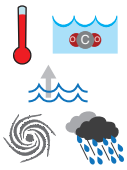
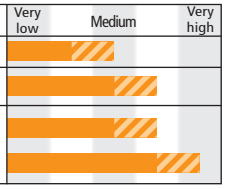
Polar Regions

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Risks for freshwater and terrestrial ecosystems (*high confidence*) and marine ecosystems (*medium confidence*), due to changes in ice, snow cover, permafrost, and freshwater/ocean conditions, affecting species' habitat quality, ranges, phenology, and productivity, as well as dependent economies [28.2-4]	• Improved understanding through scientific and indigenous knowledge, producing more effective solutions and/or technological innovations • Enhanced monitoring, regulation, and warning systems that achieve safe and sustainable use of ecosystem resources • Hunting or fishing for different species, if possible, and diversifying income sources		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Risks for the health and well-being of Arctic residents, resulting from injuries and illness from the changing physical environment, food insecurity, lack of reliable and safe drinking water, and damage to infrastructure, including infrastructure in permafrost regions (*high confidence*) [28.2-4]	• Co-production of more robust solutions that combine science and technology with indigenous knowledge • Enhanced observation, monitoring, and warning systems • Improved communications, education, and training • Shifting resource bases, land use, and/or settlement areas		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Unprecedented challenges for northern communities due to complex inter-linkages between climate-related hazards and societal factors, particularly if rate of change is faster than social systems can adapt (*high confidence*) [28.2-4]	• Co-production of more robust solutions that combine science and technology with indigenous knowledge • Enhanced observation, monitoring, and warning systems • Improved communications, education, and training • Adaptive co-management responses developed through the settlement of land claims		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high

Small Islands

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Loss of livelihoods, coastal settlements, infrastructure, ecosystem services, and economic stability (*high confidence*) [29.6, 29.8, Figure 29-4]	• Significant potential exists for adaptation in islands, but additional external resources and technologies will enhance response. • Maintenance and enhancement of ecosystem functions and services and of water and food security • Efficacy of traditional community coping strategies is expected to be substantially reduced in the future.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
The interaction of rising global mean sea level in the 21st century with high-water-level events will threaten low-lying coastal areas (*high confidence*) [29.4, Table 29-1; WGI AR5 13.5, Table 13.5]	• High ratio of coastal area to land mass will make adaptation a significant financial and resource challenge for islands. • Adaptation options include maintenance and restoration of coastal landforms and ecosystems, improved management of soils and freshwater resources, and appropriate building codes and settlement patterns.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high

Assessment Box SPM.2 Table 1 (continued)

The Ocean				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Distributional shift in fish and invertebrate species, and decrease in fisheries catch potential at low latitudes, e.g., in equatorial upwelling and coastal boundary systems and sub-tropical gyres (*high confidence*) [6.3, 30.5-6, Tables 6-6 and 30-3, Box CC-MB]	• Evolutionary adaptation potential of fish and invertebrate species to warming is limited as indicated by their changes in distribution to maintain temperatures. • Human adaptation options: Large-scale translocation of industrial fishing activities following the regional decreases (low latitude) vs. possibly transient increases (high latitude) in catch potential; Flexible management that can react to variability and change; Improvement of fish resilience to thermal stress by reducing other stressors such as pollution and eutrophication; Expansion of sustainable aquaculture and the development of alternative livelihoods in some regions.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Reduced biodiversity, fisheries abundance, and coastal protection by coral reefs due to heat-induced mass coral bleaching and mortality increases, exacerbated by ocean acidification, e.g., in coastal boundary systems and sub-tropical gyres (*high confidence*) [5.4, 6.4, 30.3, 30.5-6, Tables 6-6 and 30-3, Box CC-CR]	• Evidence of rapid evolution by corals is very limited. Some corals may migrate to higher latitudes, but entire reef systems are not expected to be able to track the high rates of temperature shifts. • Human adaptation options are limited to reducing other stresses, mainly by enhancing water quality, and limiting pressures from tourism and fishing. These options will delay human impacts of climate change by a few decades, but their efficacy will be severely reduced as thermal stress increases.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Coastal inundation and habitat loss due to sea level rise, extreme events, changes in precipitation, and reduced ecological resilience, e.g., in coastal boundary systems and sub-tropical gyres (*medium* to *high confidence*) [5.5, 30.5-6, Tables 6-6 and 30-3, Box CC-CR]	• Human adaptation options are limited to reducing other stresses, mainly by reducing pollution and limiting pressures from tourism, fishing, physical destruction, and unsustainable aquaculture. • Reducing deforestation and increasing reforestation of river catchments and coastal areas to retain sediments and nutrients • Increased mangrove, coral reef, and seagrass protection, and restoration to protect numerous ecosystem goods and services such as coastal protection, tourist value, and fish habitat		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	

C: MANAGING FUTURE RISKS AND BUILDING RESILIENCE

Managing the risks of climate change involves adaptation and mitigation decisions with implications for future generations, economies, and environments. This section evaluates adaptation as a means to build resilience and to adjust to climate-change impacts. It also considers limits to adaptation, climate-resilient pathways, and the role of transformation. See Figure SPM.8 for an overview of responses for addressing risk related to climate change.

C-1. Principles for Effective Adaptation

Adaptation is place- and context-specific, with no single approach for reducing risks appropriate across all settings (*high confidence*). Effective risk reduction and adaptation strategies consider the dynamics of vulnerability and exposure and their linkages with socioeconomic processes, sustainable development, and climate change. Specific examples of responses to climate change are presented in Table SPM.1.[67]

Adaptation planning and implementation can be enhanced through complementary actions across levels, from individuals to governments (*high confidence*). National governments can coordinate adaptation efforts of local and subnational governments, for example by protecting vulnerable groups, by supporting economic diversification, and by providing information, policy and legal frameworks, and financial support (*robust evidence*, *high agreement*). Local government and the private sector are increasingly recognized as critical to progress in adaptation, given their roles in scaling up adaptation of communities, households, and civil society and in managing risk information and financing (*medium evidence*, *high agreement*).[68]

A first step towards adaptation to future climate change is reducing vulnerability and exposure to present climate variability (*high confidence*). Strategies include actions with co-benefits for other objectives. Available strategies and actions can increase resilience across a range of possible future climates while helping to improve human health, livelihoods, social and economic well-being, and

[67] 2.1, 8.3-4, 13.1, 13.3-4, 15.2-3, 15.5, 16.2-3, 16.5, 17.2, 17.4, 19.6, 21.3, 22.4, 26.8-9, 29.6, 29.8

[68] 2.1-4, 3.6, 5.5, 8.3-4, 9.3-4, 14.2, 15.2-3, 15.5, 16.2-5, 17.2-3, 22.4, 24.4, 25.4, 26.8-9, 30.7, Tables 21-1, 21-5, & 21-6, Box 16-2

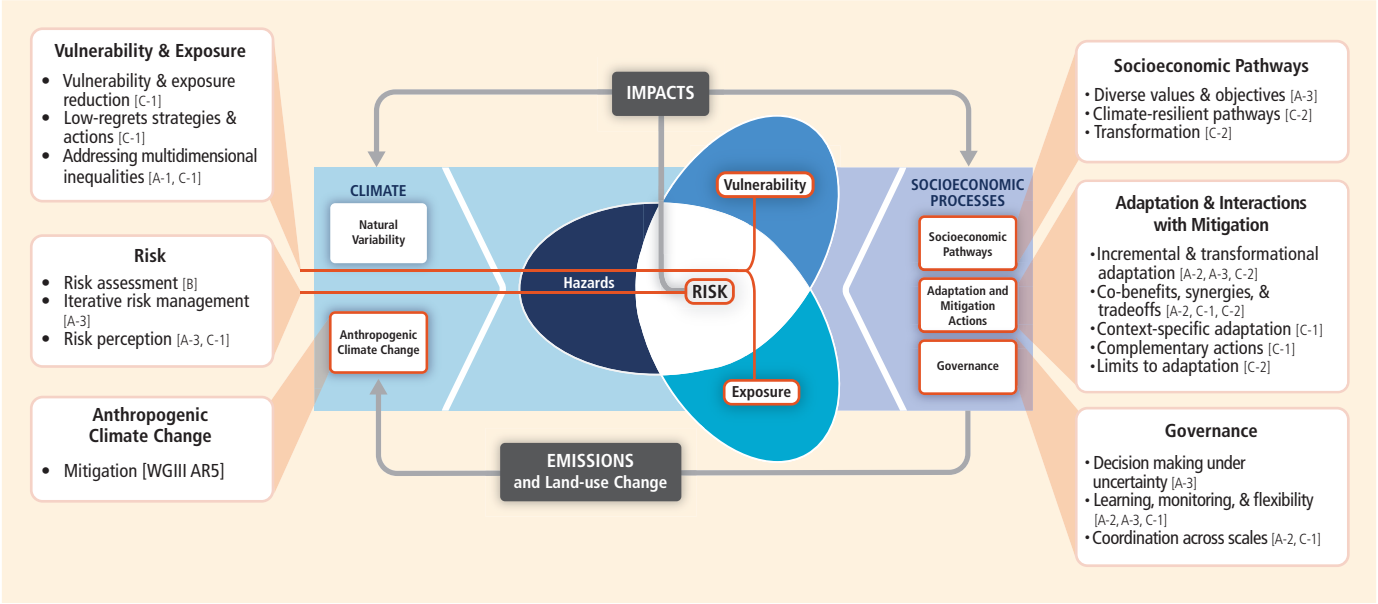


Figure SPM.8 | The solution space. Core concepts of the WGII AR5, illustrating overlapping entry points and approaches, as well as key considerations, in managing risks related to climate change, as assessed in this report and presented throughout this SPM. Bracketed references indicate sections of this summary with corresponding assessment findings.

environmental quality. See Table SPM.1. Integration of adaptation into planning and decision making can promote synergies with development and disaster risk reduction.[69]

Adaptation planning and implementation at all levels of governance are contingent on societal values, objectives, and risk perceptions (*high confidence*). Recognition of diverse interests, circumstances, social-cultural contexts, and expectations can benefit decision-making processes. Indigenous, local, and traditional knowledge systems and practices, including indigenous peoples' holistic view of community and environment, are a major resource for adapting to climate change, but these have not been used consistently in existing adaptation efforts. Integrating such forms of knowledge with existing practices increases the effectiveness of adaptation.[70]

Decision support is most effective when it is sensitive to context and the diversity of decision types, decision processes, and constituencies (*robust evidence*, *high agreement*). Organizations bridging science and decision making, including climate services, play an important role in the communication, transfer, and development of climate-related knowledge, including translation, engagement, and knowledge exchange (*medium evidence*, *high agreement*).[71]

Existing and emerging economic instruments can foster adaptation by providing incentives for anticipating and reducing impacts (*medium confidence*). Instruments include public-private finance partnerships, loans, payments for environmental services, improved resource pricing, charges and subsidies, norms and regulations, and risk sharing and transfer mechanisms. Risk financing mechanisms in the public and private sector, such as insurance and risk pools, can contribute to increasing resilience, but without attention to major design challenges, they can also provide disincentives, cause market failure, and decrease equity. Governments often play key roles as regulators, providers, or insurers of last resort.[72]

Constraints can interact to impede adaptation planning and implementation (*high confidence*). Common constraints on implementation arise from the following: limited financial and human resources; limited integration or coordination of governance; uncertainties

[69] 3.6, 8.3, 9.4, 14.3, 15.2-3, 17.2, 20.4, 20.6, 22.4, 24.4-5, 25.4, 25.10, 27.3-5, 29.6, Boxes 25-2 and 25-6
[70] 2.2-4, 9.4, 12.3, 13.2, 15.2, 16.2-4, 16.7, 17.2-3, 21.3, 22.4, 24.4, 24.6, 25.4, 25.8, 26.9, 28.2, 28.4, Table 15-1, Box 25-7
[71] 2.1-4, 8.4, 14.4, 16.2-3, 16.5, 21.2-3, 21.5, 22.4, Box 9-4
[72] 10.7, 10.9, 13.3, 17.4-5, Box 25-7

Table SPM.1 | Approaches for managing the risks of climate change. These approaches should be considered overlapping rather than discrete, and they are often pursued simultaneously. Mitigation is considered essential for managing the risks of climate change. It is not addressed in this table as mitigation is the focus of WGIII AR5. Examples are presented in no specific order and can be relevant to more than one category. [14.2-3, Table 14-1]

Overlapping Approaches	Category	Examples	Chapter Reference(s)
Vulnerability & Exposure Reduction through development, planning, & practices including many low-regrets measures	Human development	Improved access to education, nutrition, health facilities, energy, safe housing & settlement structures, & social support structures; Reduced gender inequality & marginalization in other forms.	8.3, 9.3, 13.1-3, 14.2-3, 22.4
	Poverty alleviation	Improved access to & control of local resources; Land tenure; Disaster risk reduction; Social safety nets & social protection; Insurance schemes.	8.3-4, 9.3, 13.1-3
	Livelihood security	Income, asset, & livelihood diversification; Improved infrastructure; Access to technology & decision-making fora; Increased decision-making power; Changed cropping, livestock, & aquaculture practices; Reliance on social networks.	7.5, 9.4, 13.1-3, 22.3-4, 23.4, 26.5, 27.3, 29.6, Table SM24-7
	Disaster risk management	Early warning systems; Hazard & vulnerability mapping; Diversifying water resources; Improved drainage; Flood & cyclone shelters; Building codes & practices; Storm & wastewater management; Transport & road infrastructure improvements.	8.2-4, 11.7, 14.3, 15.4, 22.4, 24.4, 26.6, 28.4, Box 25-1, Table 3-3
	Ecosystem management	Maintaining wetlands & urban green spaces; Coastal afforestation; Watershed & reservoir management; Reduction of other stressors on ecosystems & of habitat fragmentation; Maintenance of genetic diversity; Manipulation of disturbance regimes; Community-based natural resource management.	4.3-4, 8.3, 22.4, Table 3-3, Boxes 4-3, 8-2, 15-1, 25-8, 25-9, & CC-EA
	Spatial or land-use planning	Provisioning of adequate housing, infrastructure, & services; Managing development in flood prone & other high risk areas; Urban planning & upgrading programs; Land zoning laws; Easements; Protected areas.	4.4, 8.1-4, 22.4, 23.7-8, 27.3, Box 25-8
Adaptation including incremental & transformational adjustments	Structural/physical	***Engineered & built-environment options***: Sea walls & coastal protection structures; Flood levees; Water storage; Improved drainage; Flood & cyclone shelters; Building codes & practices; Storm & wastewater management; Transport & road infrastructure improvements; Floating houses; Power plant & electricity grid adjustments.	3.5-6, 5.5, 8.2-3, 10.2, 11.7, 23.3, 24.4, 25.7, 26.3, 26.8, Boxes 15-1, 25-1, 25-2, & 25-8
		Technological options: New crop & animal varieties; Indigenous, traditional, & local knowledge, technologies, & methods; Efficient irrigation; Water-saving technologies; Desalinization; Conservation agriculture; Food storage & preservation facilities; Hazard & vulnerability mapping & monitoring; Early warning systems; Building insulation; Mechanical & passive cooling; Technology development, transfer, & diffusion.	7.5, 8.3, 9.4, 10.3, 15.4, 22.4, 24.4, 26.3, 26.5, 27.3, 28.2, 28.4, 29.6-7, Boxes 20-5 & 25-2, Tables 3-3 & 15-1
		Ecosystem-based options: Ecological restoration; Soil conservation; Afforestation & reforestation; Mangrove conservation & replanting; Green infrastructure (e.g., shade trees, green roofs); Controlling overfishing; Fisheries co-management; Assisted species migration & dispersal; Ecological corridors; Seed banks, gene banks, & other *ex situ* conservation; Community-based natural resource management.	4.4, 5.5, 6.4, 8.3, 9.4, 11.7, 15.4, 22.4, 23.6-7, 24.4, 25.6, 27.3, 28.2, 29.7, 30.6, Boxes 15-1, 22-2, 25-9, 26-2, & CC-EA
		Services: Social safety nets & social protection; Food banks & distribution of food surplus; Municipal services including water & sanitation; Vaccination programs; Essential public health services; Enhanced emergency medical services.	3.5-6, 8.3, 9.3, 11.7, 11.9, 22.4, 29.6, Box 13-2
	Institutional	***Economic options***: Financial incentives; Insurance; Catastrophe bonds; Payments for ecosystem services; Pricing water to encourage universal provision and careful use; Microfinance; Disaster contingency funds; Cash transfers; Public-private partnerships.	8.3-4, 9.4, 10.7, 11.7, 13.3, 15.4, 17.5, 22.4, 26.7, 27.6, 29.6, Box 25-7
		Laws & regulations: Land zoning laws; Building standards & practices; Easements; Water regulations & agreements; Laws to support disaster risk reduction; Laws to encourage insurance purchasing; Defined property rights & land tenure security; Protected areas; Fishing quotas; Patent pools & technology transfer.	4.4, 8.3, 9.3, 10.5, 10.7, 15.2, 15.4, 17.5, 22.4, 23.4, 23.7, 24.4, 25.4, 26.3, 27.3, 30.6, Table 25-2, Box CC-CR
		National & government policies & programs: National & regional adaptation plans including mainstreaming; Sub-national & local adaptation plans; Economic diversification; Urban upgrading programs; Municipal water management programs; Disaster planning & preparedness; Integrated water resource management; Integrated coastal zone management; Ecosystem-based management; Community-based adaptation.	2.4, 3.6, 4.4, 5.5, 6.4, 7.5, 8.3, 11.7, 15.2-5, 22.4, 23.7, 25.4, 25.8, 26.8-9, 27.3-4, 29.6, Boxes 25-1, 25-2, & 25-9, Tables 9-2 & 17-1
	Social	***Educational options***: Awareness raising & integrating into education; Gender equity in education; Extension services; Sharing indigenous, traditional, & local knowledge; Participatory action research & social learning; Knowledge-sharing & learning platforms.	8.3-4, 9.4, 11.7, 12.3, 15.2-4, 22.4, 25.4, 28.4, 29.6, Tables 15-1 & 25-2
		Informational options: Hazard & vulnerability mapping; Early warning & response systems; Systematic monitoring & remote sensing; Climate services; Use of indigenous climate observations; Participatory scenario development; Integrated assessments.	2.4, 5.5, 8.3-4, 9.4, 11.7, 15.2-4, 22.4, 23.5, 24.4, 25.8, 26.6, 26.8, 27.3, 28.2, 28.5, 30.6, Table 25-2, Box 26-3
		Behavioral options: Household preparation & evacuation planning; Migration; Soil & water conservation; Storm drain clearance; Livelihood diversification; Changed cropping, livestock, & aquaculture practices; Reliance on social networks.	5.5, 7.5, 9.4, 12.4, 22.3-4, 23.4, 23.7, 25.7, 26.5, 27.3, 29.6, Table SM24-7, Box 25-5
Transformation	Spheres of change	***Practical***: Social & technical innovations, behavioral shifts, or institutional & managerial changes that produce substantial shifts in outcomes.	8.3, 17.3, 20.5, Box 25-5
		Political: Political, social, cultural, & ecological decisions & actions consistent with reducing vulnerability & risk & supporting adaptation, mitigation, & sustainable development.	14.2-3, 20.5, 25.4, 30.7, Table 14-1
		Personal: Individual & collective assumptions, beliefs, values, & worldviews influencing climate-change responses.	14.2-3, 20.5, 25.4, Table 14-1

about projected impacts; different perceptions of risks; competing values; absence of key adaptation leaders and advocates; and limited tools to monitor adaptation effectiveness. Another constraint includes insufficient research, monitoring, and observation and the finance to maintain them. Underestimating the complexity of adaptation as a social process can create unrealistic expectations about achieving intended adaptation outcomes.[73]

Poor planning, overemphasizing short-term outcomes, or failing to sufficiently anticipate consequences can result in maladaptation (*medium evidence*, *high agreement*). Maladaptation can increase the vulnerability or exposure of the target group in the future, or the vulnerability of other people, places, or sectors. Some near-term responses to increasing risks related to climate change may also limit future choices. For example, enhanced protection of exposed assets can lock in dependence on further protection measures.[74]

Limited evidence indicates a gap between global adaptation needs and the funds available for adaptation (*medium confidence*). There is a need for a better assessment of global adaptation costs, funding, and investment. Studies estimating the global cost of adaptation are characterized by shortcomings in data, methods, and coverage (*high confidence*).[75]

Significant co-benefits, synergies, and trade-offs exist between mitigation and adaptation and among different adaptation responses; interactions occur both within and across regions (*very high confidence*). Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, particularly at the intersections among water, energy, land use, and biodiversity, but tools to understand and manage these interactions remain limited. Examples of actions with co-benefits include (i) improved energy efficiency and cleaner energy sources, leading to reduced emissions of health-damaging climate-altering air pollutants; (ii) reduced energy and water consumption in urban areas through greening cities and recycling water; (iii) sustainable agriculture and forestry; and (iv) protection of ecosystems for carbon storage and other ecosystem services.[76]

C-2. Climate-resilient Pathways and Transformation

Climate-resilient pathways are sustainable-development trajectories that combine adaptation and mitigation to reduce climate change and its impacts. They include iterative processes to ensure that effective risk management can be implemented and sustained. See Figure SPM.9.[77]

Prospects for climate-resilient pathways for sustainable development are related fundamentally to what the world accomplishes with climate-change mitigation (*high confidence*). Since mitigation reduces the rate as well as the magnitude of warming, it also increases the time available for adaptation to a particular level of climate change, potentially by several decades. Delaying mitigation actions may reduce options for climate-resilient pathways in the future.[78]

Greater rates and magnitude of climate change increase the likelihood of exceeding adaptation limits (*high confidence*). Limits to adaptation occur when adaptive actions to avoid intolerable risks for an actor's objectives or for the needs of a system are not possible or are not currently available. Value-based judgments of what constitutes an intolerable risk may differ. Limits to adaptation emerge from the interaction among climate change and biophysical and/or socioeconomic constraints. Opportunities to take advantage of positive synergies between adaptation and mitigation may decrease with time, particularly if limits to adaptation are exceeded. In some parts of the world, insufficient responses to emerging impacts are already eroding the basis for sustainable development.[79]

[73] 3.6, 4.4, 5.5, 8.4, 9.4, 13.2-3, 14.2, 14.5, 15.2-3, 15.5, 16.2-3, 16.5, 17.2-3, 22.4, 23.7, 24.5, 25.4, 25.10, 26.8-9, 30.6, Table 16-3, Boxes 16-1 and 16-3
[74] 5.5, 8.4, 14.6, 15.5, 16.3, 17.2-3, 20.2, 22.4, 24.4, 25.10, 26.8, Table 14-4, Box 25-1
[75] 14.2, 17.4, Tables 17-2 and 17-3
[76] 2.4-5, 3.7, 4.2, 4.4, 5.4-5, 8.4, 9.3, 11.9, 13.3, 17.2, 19.3-4, 20.2-5, 21.4, 22.6, 23.8, 24.6, 25.6-7, 25.9, 26.8-9, 27.3, 29.6-8, Boxes 25-2, 25-9, 25-10, 30.6-7, CC-WE, and CC-RF
[77] 2.5, 20.3-4
[78] 1.1, 19.7, 20.2-3, 20.6, Figure 1-5
[79] 1.1, 11.8, 13.4, 16.2-7, 17.2, 20.2-3, 20.5-6, 25.10, 26.5, Boxes 16-1, 16-3, and 16-4

Transformations in economic, social, technological, and political decisions and actions can enable climate-resilient pathways (*high confidence*). Specific examples are presented in Table SPM.1. Strategies and actions can be pursued now that will move towards climate-resilient pathways for sustainable development, while at the same time helping to improve livelihoods, social and economic well-being, and responsible environmental management. At the national level, transformation is considered most effective when it reflects a country's own visions and approaches to achieving sustainable development in accordance with its national circumstances and priorities. Transformations to sustainability are considered to benefit from iterative learning, deliberative processes, and innovation.[80]

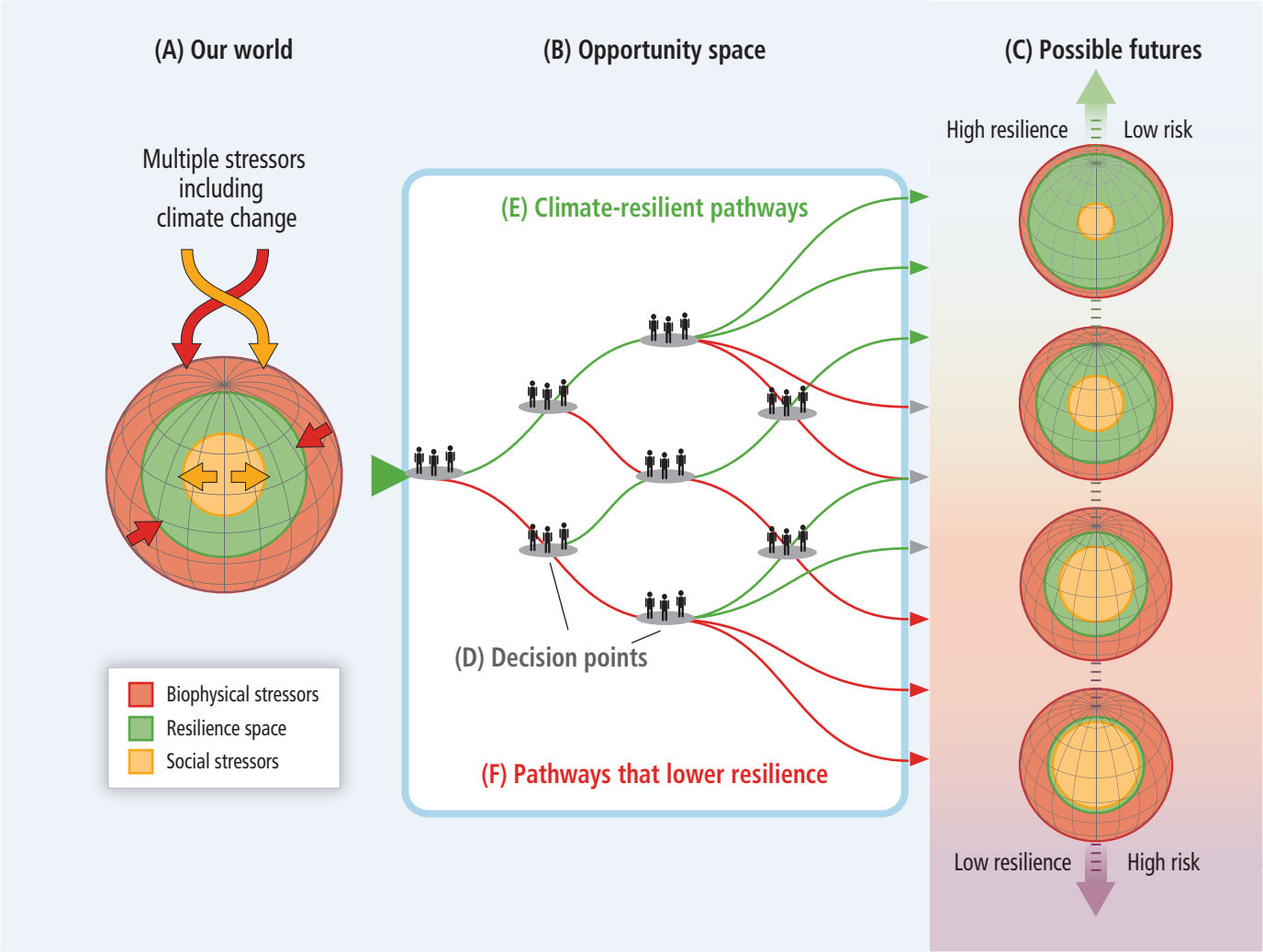


Figure SPM.9 | Opportunity space and climate-resilient pathways. (A) Our world [Sections A-1 and B-1] is threatened by multiple stressors that impinge on resilience from many directions, represented here simply as biophysical and social stressors. Stressors include climate change, climate variability, land-use change, degradation of ecosystems, poverty and inequality, and cultural factors. (B) Opportunity space [Sections A-2, A-3, B-2, C-1, and C-2] refers to decision points and pathways that lead to a range of (C) possible futures [Sections C and B-3] with differing levels of resilience and risk. (D) Decision points result in actions or failures-to-act throughout the opportunity space, and together they constitute the process of managing or failing to manage risks related to climate change. (E) Climate-resilient pathways (in green) within the opportunity space lead to a more resilient world through adaptive learning, increasing scientific knowledge, effective adaptation and mitigation measures, and other choices that reduce risks. (F) Pathways that lower resilience (in red) can involve insufficient mitigation, maladaptation, failure to learn and use knowledge, and other actions that lower resilience; and they can be irreversible in terms of possible futures.

[80] 1.1, 2.1, 2.5, 8.4, 14.1, 14.3, 16.2-7, 20.5, 22.4, 25.4, 25.10, Figure 1-5, Boxes 16-1, 16-4, and TS.8

SUPPLEMENTARY MATERIAL

Table SPM.A1 | Observed impacts attributed to climate change reported in the scientific literature since the AR4. These impacts have been attributed to climate change with *very low*, *low*, *medium*, or *high confidence*, with the relative contribution of climate change to the observed change indicated (major or minor), for natural and human systems across eight major world regions over the past several decades. [Tables 18-5, 18-6, 18-7, 18-8, and 18-9] Absence from the table of additional impacts attributed to climate change does not imply that such impacts have not occurred.

Africa	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Retreat of tropical highland glaciers in East Africa (*high confidence*, major contribution from climate change) • Reduced discharge in West African rivers (*low confidence*, major contribution from climate change) • Lake surface warming and water column stratification increases in the Great Lakes and Lake Kariba (*high confidence*, major contribution from climate change) • Increased soil moisture drought in the Sahel since 1970, partially wetter conditions since 1990 (*medium confidence*, major contribution from climate change) [22.2-3, Tables 18-5, 18-6, and 22-3]
Terrestrial Ecosystems	• Tree density decreases in western Sahel and semi-arid Morocco, beyond changes due to land use (*medium confidence*, major contribution from climate change) • Range shifts of several southern plants and animals, beyond changes due to land use (*medium confidence*, major contribution from climate change) • Increases in wildfires on Mt. Kilimanjaro (*low confidence*, major contribution from climate change) [22.3, Tables 18-7 and 22-3]
Coastal Erosion & Marine Ecosystems	• Decline in coral reefs in tropical African waters, beyond decline due to human impacts (*high confidence*, major contribution from climate change) [Table 18-8]
Food Production & Livelihoods	• Adaptive responses to changing rainfall by South African farmers, beyond changes due to economic conditions (*very low confidence*, major contribution from climate change) • Decline in fruit-bearing trees in Sahel (*low confidence*, major contribution from climate change) • Malaria increases in Kenyan highlands, beyond changes due to vaccination, drug resistance, demography, and livelihoods (*low confidence*, minor contribution from climate change) • Reduced fisheries productivity of Great Lakes and Lake Kariba, beyond changes due to fisheries management and land use (*low confidence*, minor contribution from climate change) [7.2, 11.5, 13.2, 22.3, Table 18-9]
Europe	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Retreat of Alpine, Scandinavian, and Icelandic glaciers (*high confidence*, major contribution from climate change) • Increase in rock slope failures in western Alps (*medium confidence*, major contribution from climate change) • Changed occurrence of extreme river discharges and floods (*very low confidence*, minor contribution from climate change) [18.3, 23.2-3, Tables 18-5 and 18-6; WGI AR5 4.3]
Terrestrial Ecosystems	• Earlier greening, leaf emergence, and fruiting in temperate and boreal trees (*high confidence*, major contribution from climate change) • Increased colonization of alien plant species in Europe, beyond a baseline of some invasion (*medium confidence*, major contribution from climate change) • Earlier arrival of migratory birds in Europe since 1970 (*medium confidence*, major contribution from climate change) • Upward shift in tree-line in Europe, beyond changes due to land use (*low confidence*, major contribution from climate change) • Increasing burnt forest areas during recent decades in Portugal and Greece, beyond some increase due to land use (*high confidence*, major contribution from climate change) [4.3, 18.3, Tables 18-7 and 23-6]
Coastal Erosion & Marine Ecosystems	• Northward distributional shifts of zooplankton, fishes, seabirds, and benthic invertebrates in northeast Atlantic (*high confidence*, major contribution from climate change) • Northward and depth shift in distribution of many fish species across European seas (*medium confidence*, major contribution from climate change) • Plankton phenology changes in northeast Atlantic (*medium confidence*, major contribution from climate change) • Spread of warm water species into the Mediterranean, beyond changes due to invasive species and human impacts (*medium confidence*, major contribution from climate change) [6.3, 23.6, 30.5, Tables 6-2 and 18-8, Boxes 6-1 and CC-MB]
Food Production & Livelihoods	• Shift from cold-related mortality to heat-related mortality in England and Wales, beyond changes due to exposure and health care (*low confidence*, major contribution from climate change) • Impacts on livelihoods of Sámi people in northern Europe, beyond effects of economic and sociopolitical changes (*medium confidence*, major contribution from climate change) • Stagnation of wheat yields in some countries in recent decades, despite improved technology (*medium confidence*, minor contribution from climate change) • Positive yield impacts for some crops mainly in northern Europe, beyond increase due to improved technology (*medium confidence*, minor contribution from climate change) • Spread of bluetongue virus in sheep and of ticks across parts of Europe (*medium confidence*, minor contribution from climate change) [18.4, 23.4-5, Table 18-9, Figure 7-2]

Continued next page →

Table SPM.A1 (continued)

Asia	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Permafrost degradation in Siberia, Central Asia, and Tibetan Plateau (*high confidence*, major contribution from climate change) • Shrinking mountain glaciers across most of Asia (*medium confidence*, major contribution from climate change) • Changed water availability in many Chinese rivers, beyond changes due to land use (*low confidence*, minor contribution from climate change) • Increased flow in several rivers due to shrinking glaciers (*high confidence*, major contribution from climate change) • Earlier timing of maximum spring flood in Russian rivers (*medium confidence*, major contribution from climate change) • Reduced soil moisture in north-central and northeast China (1950–2006) (*medium confidence*, major contribution from climate change) • Surface water degradation in parts of Asia, beyond changes due to land use (*medium confidence*, minor contribution from climate change) [24.3-4, 28.2, Tables 18-5, 18-6, and SM24-4, Box 3-1; WGI AR5 4.3, 10.5]
Terrestrial Ecosystems	• Changes in plant phenology and growth in many parts of Asia (earlier greening), particularly in the north and east (*medium confidence*, major contribution from climate change) • Distribution shifts of many plant and animal species upwards in elevation or polewards, particularly in the north of Asia (*medium confidence*, major contribution from climate change) • Invasion of Siberian larch forests by pine and spruce during recent decades (*low confidence*, major contribution from climate change) • Advance of shrubs into the Siberian tundra (*high confidence*, major contribution from climate change) [4.3, 24.4, 28.2, Table 18-7, Figure 4-4]
Coastal Erosion & Marine Ecosystems	• Decline in coral reefs in tropical Asian waters, beyond decline due to human impacts (*high confidence*, major contribution from climate change) • Northward range extension of corals in the East China Sea and western Pacific, and of a predatory fish in the Sea of Japan (*medium confidence*, major contribution from climate change) • Shift from sardines to anchovies in the western North Pacific, beyond fluctuations due to fisheries (*low confidence*, major contribution from climate change) • Increased coastal erosion in Arctic Asia (*low confidence*, major contribution from climate change) [6.3, 24.4, 30.5, Tables 6-2 and 18-8]
Food Production & Livelihoods	• Impacts on livelihoods of indigenous groups in Arctic Russia, beyond economic and sociopolitical changes (*low confidence*, major contribution from climate change) • Negative impacts on aggregate wheat yields in South Asia, beyond increase due to improved technology (*medium confidence*, minor contribution from climate change) • Negative impacts on aggregate wheat and maize yields in China, beyond increase due to improved technology (*low confidence*, minor contribution from climate change) • Increases in a water-borne disease in Israel (*low confidence*, minor contribution from climate change) [7.2, 13.2, 18.4, 28.2, Tables 18-4 and 18-9, Figure 7-2]
Australasia	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Significant decline in late-season snow depth at 3 of 4 alpine sites in Australia (1957–2002) (*medium confidence*, major contribution from climate change) • Substantial reduction in ice and glacier ice volume in New Zealand (*medium confidence*, major contribution from climate change) • Intensification of hydrological drought due to regional warming in southeast Australia (*low confidence*, minor contribution from climate change) • Reduced inflow in river systems in southwestern Australia (since the mid-1970s) (*high confidence*, major contribution from climate change) [25.5, Tables 18-5, 18-6, and 25-1; WGI AR5 4.3]
Terrestrial Ecosystems	• Changes in genetics, growth, distribution, and phenology of many species, in particular birds, butterflies, and plants in Australia, beyond fluctuations due to variable local climates, land use, pollution, and invasive species (*high confidence*, major contribution from climate change) • Expansion of some wetlands and contraction of adjacent woodlands in southeast Australia (*low confidence*, major contribution from climate change) • Expansion of monsoon rainforest at expense of savannah and grasslands in northern Australia (*medium confidence*, major contribution from climate change) • Migration of glass eels advanced by several weeks in Waikato River, New Zealand (*low confidence*, major contribution from climate change) [Tables 18-7 and 25-3]
Coastal Erosion & Marine Ecosystems	• Southward shifts in the distribution of marine species near Australia, beyond changes due to short-term environmental fluctuations, fishing, and pollution (*medium confidence*, major contribution from climate change) • Change in timing of migration of seabirds in Australia (*low confidence*, major contribution from climate change) • Increased coral bleaching in Great Barrier Reef and western Australian reefs, beyond effects from pollution and physical disturbance (*high confidence*, major contribution from climate change) • Changed coral disease patterns at Great Barrier Reef, beyond effects from pollution (*medium confidence*, major contribution from climate change) [6.3, 25.6, Tables 18-8 and 25-3]
Food Production & Livelihoods	• Advanced timing of wine-grape maturation in recent decades, beyond advance due to improved management (*medium confidence*, major contribution from climate change) • Shift in winter vs. summer human mortality in Australia, beyond changes due to exposure and health care (*low confidence*, major contribution from climate change) • Relocation or diversification of agricultural activities in Australia, beyond changes due to policy, markets, and short-term climate variability (*low confidence*, minor contribution from climate change) [11.4, 18.4, 25.7-8, Tables 18-9 and 25-3, Box 25-5]
North America	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Shrinkage of glaciers across western and northern North America (*high confidence*, major contribution from climate change) • Decreasing amount of water in spring snowpack in western North America (1960–2002) (*high confidence*, major contribution from climate change) • Shift to earlier peak flow in snow dominated rivers in western North America (*high confidence*, major contribution from climate change) • Increased runoff in the midwestern and northeastern US (*medium confidence*, minor contribution from climate change) [Tables 18-5 and 18-6; WGI AR5 2.6, 4.3]
Terrestrial Ecosystems	• Phenology changes and species distribution shifts upward in elevation and northward across multiple taxa (*medium confidence*, major contribution from climate change) • Increased wildfire frequency in subarctic conifer forests and tundra (*medium confidence*, major contribution from climate change) • Regional increases in tree mortality and insect infestations in forests (*low confidence*, minor contribution from climate change) • Increase in wildfire activity, fire frequency and duration, and burnt area in forests of the western US and boreal forests in Canada, beyond changes due to land use and fire management (*medium confidence*, minor contribution from climate change) [26.4, 28.2, Table 18-7, Box 26-2]
Coastal Erosion & Marine Ecosystems	• Northward distributional shifts of northwest Atlantic fish species (*high confidence*, major contribution from climate change) • Changes in musselbeds along the west coast of US (*high confidence*, major contribution from climate change) • Changed migration and survival of salmon in northeast Pacific (*high confidence*, major contribution from climate change) • Increased coastal erosion in Alaska and Canada (*medium confidence*, major contribution from climate change) [18.3, 30.5, Tables 6-2 and 18-8]
Food Production & Livelihoods	• Impacts on livelihoods of indigenous groups in the Canadian Arctic, beyond effects of economic and sociopolitical changes (*medium confidence*, major contribution from climate change) [18.4, 28.2, Tables 18-4 and 18-9]

Continued next page →

Table SPM.A1 (continued)

Central and South America	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Shrinkage of Andean glaciers (*high confidence*, major contribution from climate change) • Changes in extreme flows in Amazon River (*medium confidence*, major contribution from climate change) • Changing discharge patterns in rivers in the western Andes (*medium confidence*, major contribution from climate change) • Increased streamflow in sub-basins of the La Plata River, beyond increase due to land-use change (*high confidence*, major contribution from climate change) [27.3, Tables 18-5, 18-6, and 27-3; WGI AR5 4.3]
Terrestrial Ecosystems	• Increased tree mortality and forest fire in the Amazon (*low confidence*, minor contribution from climate change) • Rainforest degradation and recession in the Amazon, beyond reference trends in deforestation and land degradation (*low confidence*, minor contribution from climate change) [4.3, 18.3, 27.2-3, Table 18-7]
Coastal Erosion & Marine Ecosystems	• Increased coral bleaching in western Caribbean, beyond effects from pollution and physical disturbance (*high confidence*, major contribution from climate change) • Mangrove degradation on north coast of South America, beyond degradation due to pollution and land use (*low confidence*, minor contribution from climate change) [27.3, Table 18-8]
Food Production & Livelihoods	• More vulnerable livelihood trajectories for indigenous Aymara farmers in Bolivia due to water shortage, beyond effects of increasing social and economic stress (*medium confidence*, major contribution from climate change) • Increase in agricultural yields and expansion of agricultural areas in southeastern South America, beyond increase due to improved technology (*medium confidence*, major contribution from climate change) [13.1, 27.3, Table 18-9]
Polar Regions	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Decreasing Arctic sea ice cover in summer (*high confidence*, major contribution from climate change) • Reduction in ice volume in Arctic glaciers (*high confidence*, major contribution from climate change) • Decreasing snow cover extent across the Arctic (*medium confidence*, major contribution from climate change) • Widespread permafrost degradation, especially in the southern Arctic (*high confidence*, major contribution from climate change) • Ice mass loss along coastal Antarctica (*medium confidence*, major contribution from climate change) • Increased river discharge for large circumpolar rivers (1997–2007) (*low confidence*, major contribution from climate change) • Increased winter minimum river flow in most of the Arctic (*medium confidence*, major contribution from climate change) • Increased lake water temperatures 1985–2009 and prolonged ice-free seasons (*medium confidence*, major contribution from climate change) • Disappearance of thermokarst lakes due to permafrost degradation in the low Arctic. New lakes created in areas of formerly frozen peat (*high confidence*, major contribution from climate change) [28.2, Tables 18-5 and 18-6; WGI AR5 4.2-4, 4.6, 10.5]
Terrestrial Ecosystems	• Increased shrub cover in tundra in North America and Eurasia (*high confidence*, major contribution from climate change) • Advance of Arctic tree-line in latitude and altitude (*medium confidence*, major contribution from climate change) • Changed breeding area and population size of subarctic birds, due to snowbed reduction and/or tundra shrub encroachment (*medium confidence*, major contribution from climate change) • Loss of snow-bed ecosystems and tussock tundra (*high confidence*, major contribution from climate change) • Impacts on tundra animals from increased ice layers in snow pack, following rain-on-snow events (*medium confidence*, major contribution from climate change) • Increased plant species ranges in the West Antarctic Peninsula and nearby islands over the past 50 years (*high confidence*, major contribution from climate change) • Increased phytoplankton productivity in Signy Island lake waters (*high confidence*, major contribution from climate change) [28.2, Table 18-7]
Coastal Erosion & Marine Ecosystems	• Increased coastal erosion across Arctic (*medium confidence*, major contribution from climate change) • Negative effects on non-migratory Arctic species (*high confidence*, major contribution from climate change) • Decreased reproductive success in Arctic seabirds (*medium confidence*, major contribution from climate change) • Decline in Southern Ocean seals and seabirds (*medium confidence*, major contribution from climate change) • Reduced thickness of foraminiferal shells in southern oceans, due to ocean acidification (*medium confidence*, major contribution from climate change) • Reduced krill density in Scotia Sea (*medium confidence*, major contribution from climate change) [6.3, 18.3, 28.2-3, Table 18-8]
Food Production & Livelihoods	• Impact on livelihoods of Arctic indigenous peoples, beyond effects of economic and sociopolitical changes (*medium confidence*, major contribution from climate change) • Increased shipping traffic across the Bering Strait (*medium confidence*, major contribution from climate change) [18.4, 28.2, Tables 18-4 and 18-9, Figure 28-4]
Small Islands	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Increased water scarcity in Jamaica, beyond increase due to water use (*very low confidence*, minor contribution from climate change) [Table 18-6]
Terrestrial Ecosystems	• Tropical bird population changes in Mauritius (*medium confidence*, major contribution from climate change) • Decline of an endemic plant in Hawai'i (*medium confidence*, major contribution from climate change) • Upward trend in tree-lines and associated fauna on high-elevation islands (*low confidence*, minor contribution from climate change) [29.3, Table 18-7]
Coastal Erosion & Marine Ecosystems	• Increased coral bleaching near many tropical small islands, beyond effects of degradation due to fishing and pollution (*high confidence*, major contribution from climate change) • Degradation of mangroves, wetlands, and seagrass around small islands, beyond degradation due to other disturbances (*very low confidence*, minor contribution from climate change) • Increased flooding and erosion, beyond erosion due to human activities, natural erosion, and accretion (*low confidence*, minor contribution from climate change) • Degradation of groundwater and freshwater ecosystems due to saline intrusion, beyond degradation due to pollution and groundwater pumping (*low confidence*, minor contribution from climate change) [29.3, Table 18-8]
Food Production & Livelihoods	• Increased degradation of coastal fisheries due to direct effects and effects of increased coral reef bleaching, beyond degradation due to overfishing and pollution (*low confidence*, minor contribution from climate change) [18.3-4, 29.3, 30.6, Table 18-9, Box CC-CR]

Technical Summary

TS

Technical Summary

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This Technical Summary should be cited as:

Field, C.B., V.R. Barros, K.J. Mach, M.D. Mastrandrea, M. van Aalst, W.N. Adger, D.J. Arent, J. Barnett, R. Betts, T.E. Bilir, J. Birkmann, J. Carmin, D.D. Chadee, A.J. Challinor, M. Chatterjee, W. Cramer, D.J. Davidson, Y.O. Estrada, J.-P. Gattuso, Y. Hijioka, O. Hoegh-Guldberg, H.Q. Huang, G.E. Insarov, R.N. Jones, R.S. Kovats, P. Romero-Lankao, J.N. Larsen, I.J. Losada, J.A. Marengo, R.F. McLean, L.O. Mearns, R. Mechler, J.F. Morton, I. Niang, T. Oki, J.M. Olwoch, M. Opondo, E.S. Poloczanska, H.-O. Pörtner, M.H. Redsteer, A. Reisinger, A. Revi, D.N. Schmidt, M.R. Shaw, W. Solecki, D.A. Stone, J.M.R. Stone, K.M. Strzepek, A.G. Suarez, P. Tschakert, R. Valentini, S. Vicuña, A. Villamizar, K.E. Vincent, R. Warren, L.L. White, T.J. Wilbanks, P.P. Wong, and G.W. Yohe, 2014: Technical summary. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 35-94.

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ASSESSING AND MANAGING THE RISKS OF CLIMATE CHANGE

Human interference with the climate system is occurring (WGI AR5 SPM Section D.3; WGI AR5 Sections 2.2, 6.3, 10.3 to 10.6, 10.9). Climate change poses risks for human and natural systems (Figure TS.1). The assessment of impacts, adaptation, and vulnerability in the Working Group II contribution to the IPCC's Fifth Assessment Report (WGII AR5) evaluates how patterns of risks and potential benefits are shifting due to climate change. It considers how impacts and risks related to climate change can be reduced and managed through adaptation and mitigation. The report assesses needs, options, opportunities, constraints, resilience, limits, and other aspects associated with adaptation. It recognizes that risks of climate change will vary across regions and populations, through space and time, dependent on myriad factors including the extent of adaptation and mitigation.

Climate change involves complex interactions and changing likelihoods of diverse impacts. A focus on risk, which is new in this report, supports decision making in the context of climate change and complements other elements of the report. People and societies may perceive or rank risks and potential benefits differently, given diverse values and goals.

Compared to past WGII reports, the WGII AR5 assesses a substantially larger knowledge base of relevant scientific, technical, and socioeconomic literature. Increased literature has facilitated comprehensive assessment across a broader set of topics and sectors, with expanded coverage of human systems, adaptation, and the ocean. See Box TS.1.

Section A of this summary characterizes observed impacts, vulnerability and exposure, and adaptive responses to date. Section B examines future risks and potential benefits across sectors and regions, highlighting where choices matter for reducing risks through mitigation and adaptation. Section C considers principles for effective adaptation and the broader interactions among adaptation, mitigation, and sustainable development.

Box TS.2 defines central concepts. To convey the degree of certainty in key findings, the report relies on the consistent use of calibrated uncertainty language, introduced in Box TS.3. Chapter references in brackets indicate support for findings, figures, and tables in this summary.

A: OBSERVED IMPACTS, VULNERABILITY, AND ADAPTATION IN A COMPLEX AND CHANGING WORLD

This section presents observed effects of climate change, building from understanding of vulnerability, exposure, and climate-related hazards as determinants of impacts. The section considers the factors, including development and non-climatic stressors, that influence vulnerability and

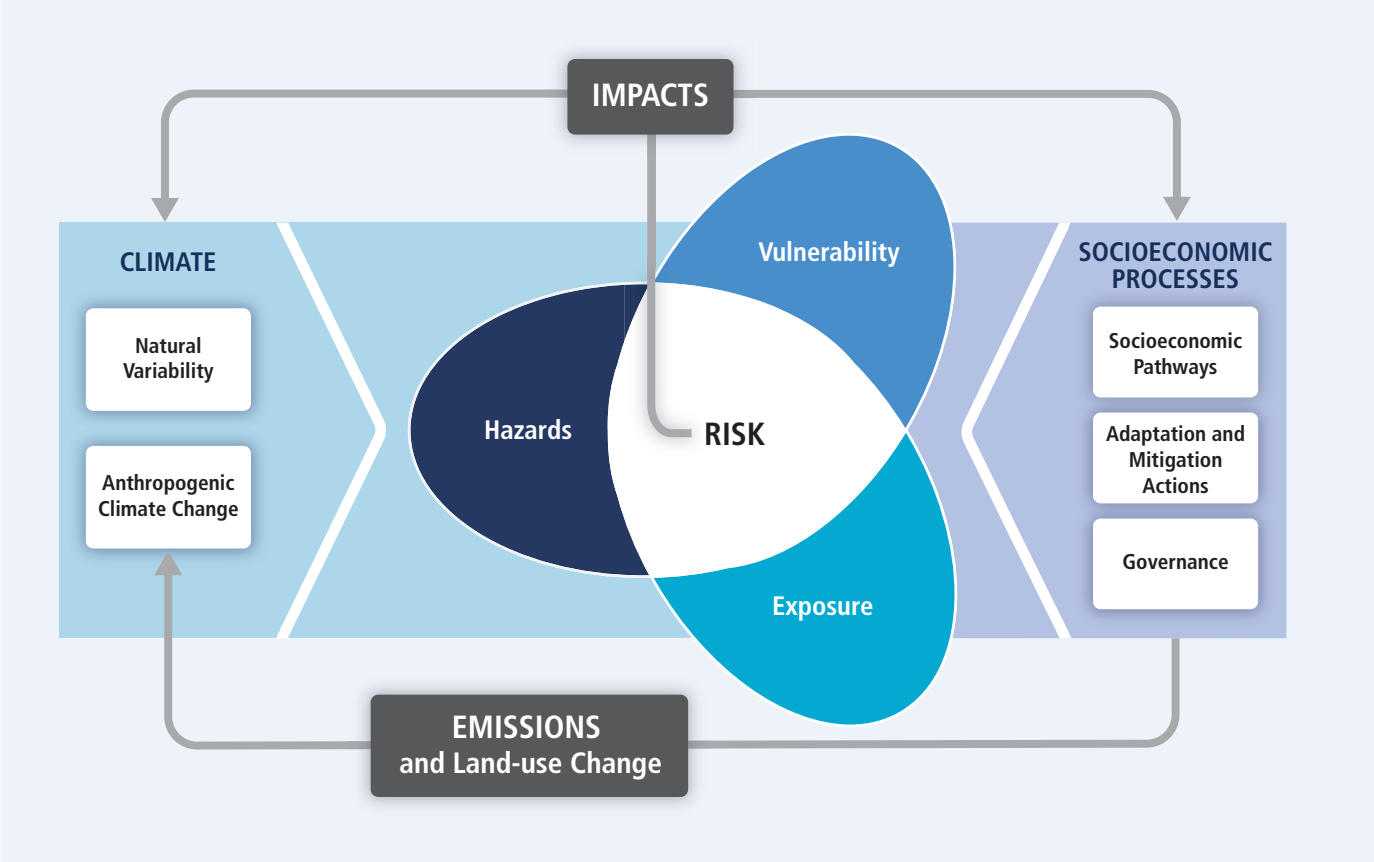
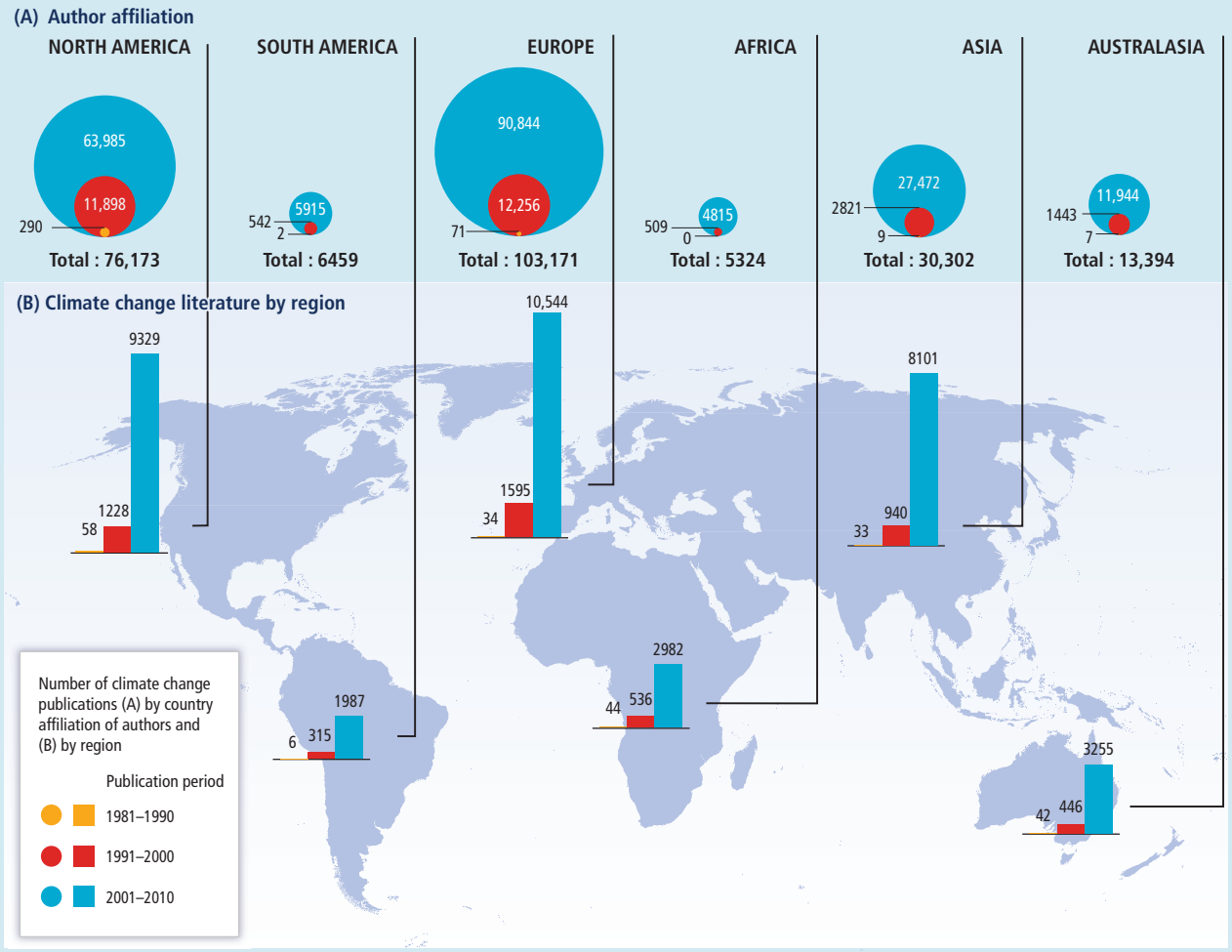


Figure TS.1 | Illustration of the core concepts of the WGII AR5. Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems. Changes in both the climate system (left) and socioeconomic processes including adaptation and mitigation (right) are drivers of hazards, exposure, and vulnerability. [19.2, Figure 19-1]

Box TS.1 | Context for the Assessment

For the past 2 decades, IPCC's Working Group II has developed assessments of climate change impacts, adaptation, and vulnerability. The WGII AR5 builds from the WGII contribution to the IPCC's Fourth Assessment Report (WGII AR4), published in 2007, and the *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX), published in 2012. It follows the Working Group I contribution to the AR5 (WGI AR5). The WGII AR5 is presented in two parts (Part A: Global and Sectoral Aspects, and Part B: Regional Aspects), reflecting the expanded literature basis and multidisciplinary approach, increased focus on societal impacts and responses, and continued regionally comprehensive coverage. [1.1 to 1.3]

The number of scientific publications available for assessing climate change impacts, adaptation, and vulnerability more than doubled between 2005 and 2010, with especially rapid increases in publications related to adaptation, allowing for a more robust assessment that supports policymaking (*high confidence*). The diversity of the topics and regions covered has similarly expanded, as has the geographic distribution of authors contributing to the knowledge base for climate change assessments (Box TS.1 Figure 1). Authorship of climate change publications from developing countries has increased, although it still represents a small fraction of the total. The unequal distribution of publications presents a challenge to the production of a comprehensive and balanced global assessment. [1.1, Figure 1-1]



Box TS.1 Figure 1 | Number of climate change publications listed in the Scopus bibliographic database. (A) Number of climate change publications in English (as of July 2011) summed by country affiliation of all authors of the publications and sorted by region. Each publication can be counted multiple times (i.e., the number of different countries in the author affiliation list). (B) Number of climate change publications in English with individual countries mentioned in title, abstract, or key words (as of July 2011) sorted by region for the decades 1981–1990, 1991–2000, and 2001–2010. Each publication can be counted multiple times if more than one country is listed. [Figure 1-1]

Continued next page →

Box TS.1 (continued)

Adaptation has emerged as a central area in climate change research, in country-level planning, and in implementation of climate change strategies (*high confidence*). The body of literature, including government and private sector reports, shows an increased focus on adaptation opportunities and the interrelations between adaptation, mitigation, and alternative sustainable pathways. The literature shows an emergence of studies on transformative processes that take advantage of synergies between adaptation planning, development strategies, social protection, and disaster risk reduction and management. [1.1]

As a core feature and innovation of IPCC assessment, major findings are presented with defined, calibrated language that communicates the strength of scientific understanding, including uncertainties and areas of disagreement (Box TS.3). Each finding is supported by a traceable account of the evaluation of evidence and agreement. [1.1, Box 1-1]

Box TS.2 | Terms Central for Understanding the Summary

Central concepts defined in the WGII AR5 glossary and used throughout the report include the following terms. Reflecting progress in science, some definitions differ in breadth and focus from the definitions used in the AR4 and other IPCC reports.

Climate change: Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes.

Hazard: The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In this report, the term *hazard* usually refers to climate-related physical events or trends or their physical impacts.

Exposure: The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.

Vulnerability: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Impacts: Effects on natural and human systems. In this report, the term *impacts* is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as *consequences* and *outcomes*. The impacts of climate change on geophysical systems, including floods, droughts, and sea level rise, are a subset of impacts called physical impacts.

Continued next page →

Box TS.2 (continued)

Risk: The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure, and hazard (see Figure TS.1). In this report, the term *risk* is used primarily to refer to the risks of climate-change impacts.

Adaptation: The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.

Incremental adaptation: Adaptation actions where the central aim is to maintain the essence and integrity of a system or process at a given scale.

Transformational adaptation: Adaptation that changes the fundamental attributes of a system in response to climate and its effects.

Transformation: A change in the fundamental attributes of natural and human systems.

Resilience: The capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation.

exposure, evaluating the sensitivity of systems to climate change. The section also identifies challenges and options based on adaptation experience, looking at what has motivated previous adaptation actions in the context of climate change and broader objectives. It examines current understanding of decision making as relevant to climate change.

A-1. Observed Impacts, Vulnerability, and Exposure

In recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. This conclusion is strengthened by more numerous and improved observations and analyses since the AR4. Evidence of climate-change impacts is strongest and most comprehensive for natural systems. Some impacts on human systems have also been attributed to climate change, with a major or minor contribution of climate change distinguishable from other influences such as changing social and economic factors. In many regions, impacts on natural and human systems are now detected even in the presence of strong confounding factors such as pollution or land use change. See Figure TS.2 and Table TS.1 for a summary of observed impacts, illustrating broader trends presented in this section. Attribution of observed impacts in the WGII AR5 generally links responses of natural and human systems to observed climate change, regardless of its cause. Most reported impacts of climate change are attributed to warming and/or to shifts in precipitation patterns. There is also emerging evidence of impacts of ocean acidification. Relatively few robust attribution studies and meta-analyses have linked impacts in physical and biological systems to anthropogenic climate change. [18.1, 18.3 to 18.6]

Differences in vulnerability and exposure arise from non-climatic factors and from multidimensional inequalities often produced by uneven development processes (*very high confidence*). These differences shape differential risks from climate change. See Figure TS.1 and Box TS.4. Vulnerability and exposure vary over time and across geographic contexts. Changes in poverty or socioeconomic status, ethnic composition, age structure, and governance have had a significant influence on the outcome of past crises associated with climate-related hazards. [8.2, 9.3, 12.2, 13.1, 13.2, 14.1 to 14.3, 19.2, 19.6, 26.8, Box CC-GC]

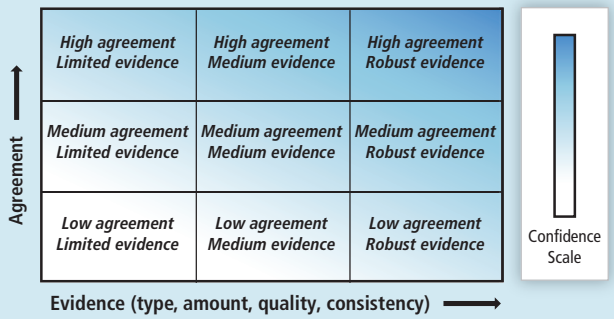
Impacts from recent climate-related extremes, such as heat waves, droughts, floods, cyclones, and wildfires, reveal significant vulnerability and exposure of some ecosystems and many human systems to current climate variability (*very high confidence*). Impacts of such climate-related extremes include alteration of ecosystems, disruption of food production and water supply, damage to infrastructure and settlements, morbidity and mortality, and consequences for mental health and human well-being. For countries at all levels of development, these impacts are consistent with a significant lack of preparedness for current climate variability in some sectors. The following examples

Box TS.3 | Communication of the Degree of Certainty in Assessment Findings

Based on the Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties, the WGII AR5 relies on two metrics for communicating the degree of certainty in key findings:

- Confidence in the validity of a finding, based on the type, amount, quality, and consistency of evidence (e.g., data, mechanistic understanding, theory, models, expert judgment) and the degree of agreement. Confidence is expressed qualitatively.
- Quantified measures of uncertainty in a finding expressed probabilistically (based on statistical analysis of observations or model results, or both, and expert judgment).

Each finding has its foundation in evaluation of associated evidence and agreement. The summary terms to describe evidence are: *limited*, *medium*, or *robust*; and agreement: *low*, *medium*, or *high*. These terms are presented with some key findings. In many cases, assessment authors in addition evaluate their confidence about the validity of a finding, providing a synthesis of the evaluation of evidence and agreement. Levels of confidence include five qualifiers: *very low*, *low*, *medium*, *high*, and *very high*. Box TS.3 Figure 1 illustrates the flexible relationship between the summary terms for evidence and agreement and the confidence metric. For a given evidence and agreement statement, different confidence levels could be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.



Box TS.3 Figure 1 | Evidence and agreement statements and their relationship to confidence. The shading increasing toward the top right corner indicates increasing confidence. Generally, evidence is most robust when there are multiple, consistent independent lines of high-quality evidence. [Figure 1-3]

When assessment authors evaluate the likelihood, or probability, of some well-defined outcome having occurred or occurring in the future, a finding can include likelihood terms (see below) or a more precise presentation of probability. Use of likelihood is not an alternative to use of confidence. Unless otherwise indicated, findings assigned a likelihood term are associated with *high* or *very high* confidence.

Term	Likelihood of the outcome
Virtually certain	99–100% probability
Extremely likely	95–100% probability
Very likely	90–100% probability
Likely	66–100% probability
More likely than not	>50–100% probability
About as likely as not	33–66% probability
Unlikely	0–33% probability
Very unlikely	0–10% probability
Extremely unlikely	0–5% probability
Exceptionally unlikely	0–1% probability

Where appropriate, findings are also formulated as statements of fact without using uncertainty qualifiers.

Within paragraphs of this summary, the confidence, evidence, and agreement terms given for a key finding apply to subsequent statements in the paragraph, unless additional terms are provided.

[1.1, Box 1-1]

illustrate impacts of extreme weather and climate events experienced across regional contexts:

- In Africa, extreme weather and climate events including droughts and floods have significant impacts on economic sectors, natural resources, ecosystems, livelihoods, and human health. The floods of the Zambezi River in Mozambique in 2008, for example, displaced 90,000 people, and along the Zambezi River Valley, with approximately 1 million people living in the flood-affected areas, temporary displacement is taking on permanent characteristics. [22.3, 22.4, 22.6]
- Recent floods in Australia and New Zealand caused severe damage to infrastructure and settlements and 35 deaths in Queensland alone (2011). The Victorian heat wave (2009) increased heat-related morbidity and was associated with more than 300 excess deaths, while intense bushfires destroyed more than 2000 buildings and led to 173 deaths. Widespread drought in southeast Australia (1997–2009) and many parts of New Zealand (2007–2009; 2012–2013) resulted in economic losses (e.g., regional GDP in the southern Murray-Darling Basin was below forecast by about 5.7% in 2007–2008, and New Zealand lost about NZ$3.6 billion in direct and off-farm output in 2007–2009). [13.2, 25.6, 25.8, Table 25-1, Boxes 25-5, 25-6, and 25-8]
- In Europe, extreme weather events currently have significant impacts in multiple economic sectors as well as adverse social and health effects (*high confidence*). [Table 23-1]
- In North America, most economic sectors and human systems have been affected by and have responded to extreme weather, including hurricanes, flooding, and intense rainfall (*high confidence*). Extreme heat events currently result in increases in mortality and morbidity (*very high confidence*), with impacts that vary by age, location, and socioeconomic factors (*high confidence*). Extreme coastal storm events have caused excess mortality and morbidity, particularly along the east coast of the United States, and the gulf coast of both Mexico and the United States. Much North American infrastructure is currently vulnerable to extreme weather events (*medium confidence*), with deteriorating water-resource and transportation infrastructure particularly vulnerable (*high confidence*). [26.6, 26.7, Figure 26-2]
- In the Arctic, extreme weather events have had direct and indirect adverse health effects for residents (*high confidence*). [28.2]

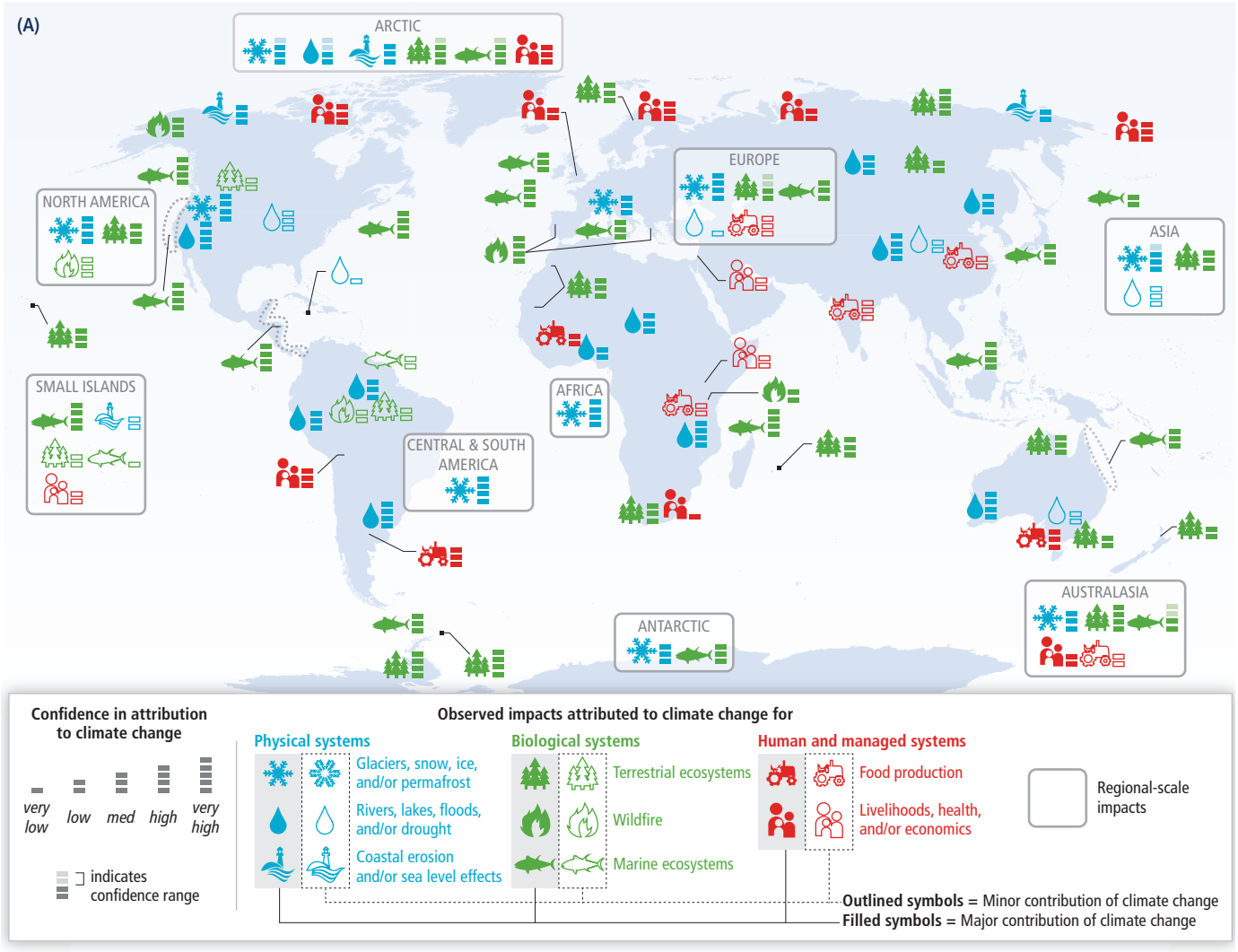


Figure TS.2

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Figure TS.2 (continued)

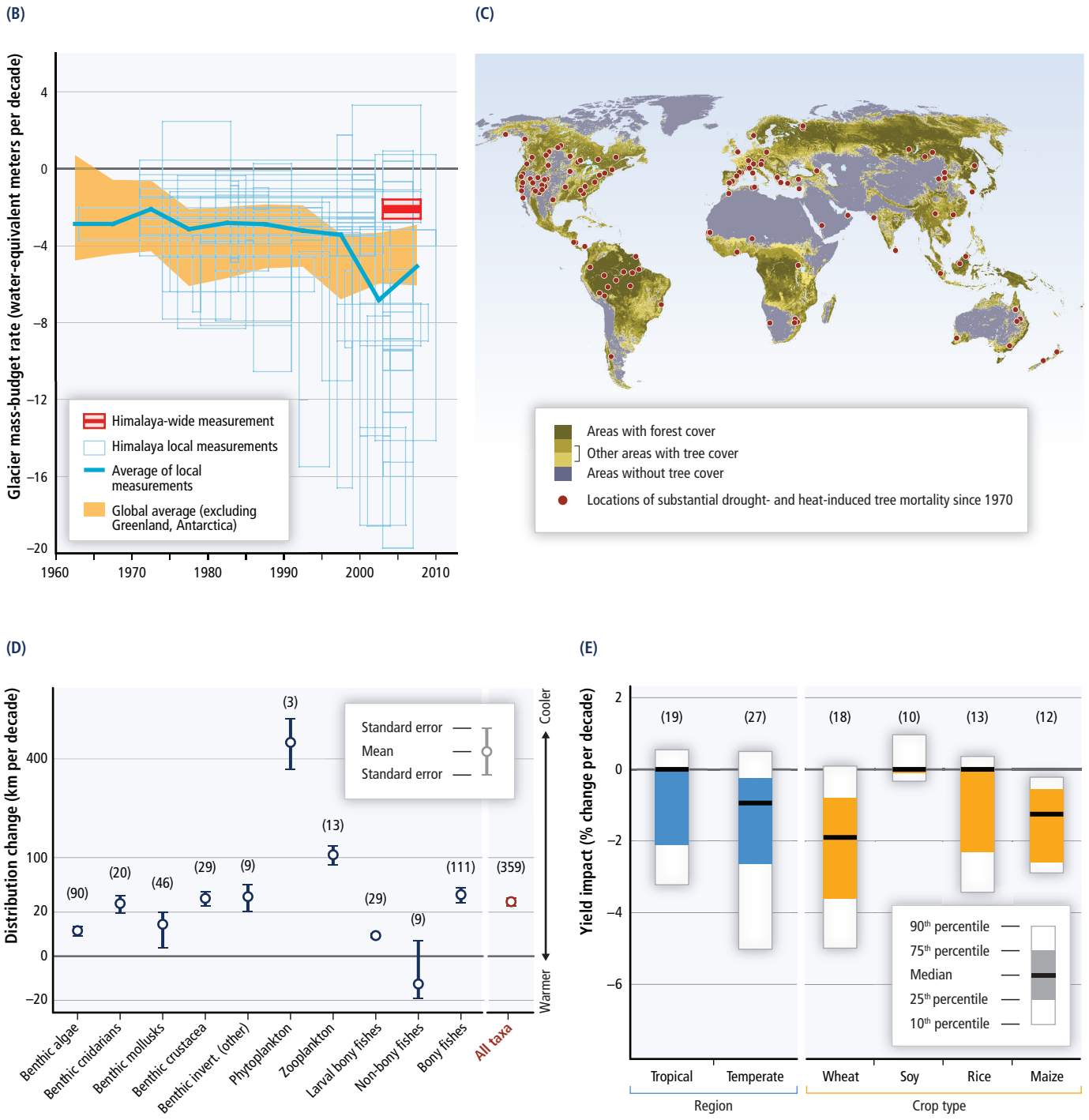


Figure TS.2 | Widespread impacts in a changing world. (A) Global patterns of impacts in recent decades attributed to climate change, based on studies since the AR4. Impacts are shown at a range of geographic scales. Symbols indicate categories of attributed impacts, the relative contribution of climate change (major or minor) to the observed impact, and confidence in attribution. See Table TS.1 for descriptions of the impacts. (B) Changes in glacier mass from all published measurements for Himalayan glaciers. Negative values indicate loss of glacier mass. Local measurements are mostly for small, accessible Himalayan glaciers. The blue box for each local Himalaya measurement is centered vertically on its average, and has a height of ±1 standard deviation for annual measurements and a height of ±1 standard error for multiannual measurements. Himalaya-wide measurement (red) was made by satellite laser altimetry. For reference, global average glacier mass change estimates from WGI AR5 4.3 are also shown, with shading indicating ±1 standard deviation. (C) Locations of substantial drought- and heat-induced tree mortality around the globe over 1970–2011. (D) Average rates of change in distribution (km per decade) for marine taxonomic groups based on observations over 1900–2010. Positive distribution changes are consistent with warming (moving into previously cooler waters, generally poleward). The number of responses analyzed is given within parentheses for each category. (E) Summary of estimated impacts of observed climate changes on yields over 1960–2013 for four major crops in temperate and tropical regions, with the number of data points analyzed given within parentheses for each category. [Figures 3-3, 4-7, 7-2, 18-3, and MB-2]

Freshwater Resources

In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality (*medium confidence*). Glaciers continue to shrink almost worldwide due to climate change (*high confidence*) (e.g., Figure TS.2B), affecting runoff and water resources downstream (*medium confidence*). Climate change is causing permafrost warming and thawing in high-latitude regions and in high-elevation regions (*high confidence*). There is no evidence that surface water and groundwater drought frequency has changed over the last few decades, although impacts of drought have increased mostly due to increased water demand. [3.2, 4.3, 18.3, 18.5, 24.4, 25.5, 26.2, 28.2, Tables 3-1 and 25-1, Figures 18-2 and 26-1]

Terrestrial and Freshwater Ecosystems

Many terrestrial and freshwater plant and animal species have shifted their geographic ranges and seasonal activities and altered their abundance in response to observed climate change over recent decades, and they are doing so now in many regions (*high confidence*). Increased tree mortality, observed in many places worldwide, has been attributed to climate change in some regions (Figure TS.2C). Increases in the frequency or intensity of ecosystem disturbances such as droughts, wind storms, fires, and pest outbreaks have been detected in many parts of the world and in some cases are attributed to climate change (*medium confidence*). While recent climate change contributed to the extinction of some species of Central American amphibians (*medium confidence*), most recent observed terrestrial

Table TS.1 | Observed impacts attributed to climate change reported in the scientific literature since the AR4. These impacts have been attributed to climate change with *very low*, *low*, *medium*, or *high confidence*, with the relative contribution of climate change to the observed change indicated (major or minor), for natural and human systems across eight major world regions over the past several decades. [Tables 18-5 to 18-9] Absence from the table of additional impacts attributed to climate change does not imply that such impacts have not occurred.

Africa	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Retreat of tropical highland glaciers in East Africa (*high confidence*, major contribution from climate change) • Reduced discharge in West African rivers (*low confidence*, major contribution from climate change) • Lake surface warming and water column stratification increases in the Great Lakes and Lake Kariba (*high confidence*, major contribution from climate change) • Increased soil moisture drought in the Sahel since 1970, partially wetter conditions since 1990 (*medium confidence*, major contribution from climate change) [22.2, 22.3, Tables 18-5, 18-6, and 22-3]
Terrestrial Ecosystems	• Tree density decreases in western Sahel and semi-arid Morocco, beyond changes due to land use (*medium confidence*, major contribution from climate change) • Range shifts of several southern plants and animals, beyond changes due to land use (*medium confidence*, major contribution from climate change) • Increases in wildfires on Mt. Kilimanjaro (*low confidence*, major contribution from climate change) [22.3, Tables 18-7 and 22-3]
Coastal Erosion & Marine Ecosystems	• Decline in coral reefs in tropical African waters, beyond decline due to human impacts (*high confidence*, major contribution from climate change) [Table 18-8]
Food Production & Livelihoods	• Adaptive responses to changing rainfall by South African farmers, beyond changes due to economic conditions (*very low confidence*, major contribution from climate change) • Decline in fruit-bearing trees in Sahel (*low confidence*, major contribution from climate change) • Malaria increases in Kenyan highlands, beyond changes due to vaccination, drug resistance, demography, and livelihoods (*low confidence*, minor contribution from climate change) • Reduced fisheries productivity of Great Lakes and Lake Kariba, beyond changes due to fisheries management and land use (*low confidence*, minor contribution from climate change) [7.2, 11.5, 13.2, 22.3, Table 18-9]
Europe	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Retreat of Alpine, Scandinavian, and Icelandic glaciers (*high confidence*, major contribution from climate change) • Increase in rock slope failures in western Alps (*medium confidence*, major contribution from climate change) • Changed occurrence of extreme river discharges and floods (*very low confidence*, minor contribution from climate change) [18.3, 23.2, 23.3, Tables 18-5 and 18-6; WGI AR5 4.3]
Terrestrial Ecosystems	• Earlier greening, leaf emergence, and fruiting in temperate and boreal trees (*high confidence*, major contribution from climate change) • Increased colonization of alien plant species in Europe, beyond a baseline of some invasion (*medium confidence*, major contribution from climate change) • Earlier arrival of migratory birds in Europe since 1970 (*medium confidence*, major contribution from climate change) • Upward shift in tree-line in Europe, beyond changes due to land use (*low confidence*, major contribution from climate change) • Increasing burnt forest areas during recent decades in Portugal and Greece, beyond some increase due to land use (*high confidence*, major contribution from climate change) [4.3, 18.3, Tables 18-7 and 23-6]
Coastal Erosion & Marine Ecosystems	• Northward distributional shifts of zooplankton, fishes, seabirds, and benthic invertebrates in northeast Atlantic (*high confidence*, major contribution from climate change) • Northward and depth shift in distribution of many fish species across European seas (*medium confidence*, major contribution from climate change) • Plankton phenology changes in northeast Atlantic (*medium confidence*, major contribution from climate change) • Spread of warm water species into the Mediterranean, beyond changes due to invasive species and human impacts (*medium confidence*, major contribution from climate change) [6.3, 23.6, 30.5, Tables 6-2 and 18-8, Boxes 6-1 and CC-MB]
Food Production & Livelihoods	• Shift from cold-related mortality to heat-related mortality in England and Wales, beyond changes due to exposure and health care (*low confidence*, major contribution from climate change) • Impacts on livelihoods of Sámi people in northern Europe, beyond effects of economic and sociopolitical changes (*medium confidence*, major contribution from climate change) • Stagnation of wheat yields in some countries in recent decades, despite improved technology (*medium confidence*, minor contribution from climate change) • Positive yield impacts for some crops mainly in northern Europe, beyond increase due to improved technology (*medium confidence*, minor contribution from climate change) • Spread of bluetongue virus in sheep and of ticks across parts of Europe (*medium confidence*, minor contribution from climate change) [18.4, 23.4, 23.5, Table 18-9, Figure 7-2]

Continued next page →

Table TS.1 (continued)

Asia	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Permafrost degradation in Siberia, Central Asia, and Tibetan Plateau (*high confidence*, major contribution from climate change) • Shrinking mountain glaciers across most of Asia (*medium confidence*, major contribution from climate change) • Changed water availability in many Chinese rivers, beyond changes due to land use (*low confidence*, minor contribution from climate change) • Increased flow in several rivers due to shrinking glaciers (*high confidence*, major contribution from climate change) • Earlier timing of maximum spring flood in Russian rivers (*medium confidence*, major contribution from climate change) • Reduced soil moisture in north-central and northeast China (1950–2006) (*medium confidence*, major contribution from climate change) • Surface water degradation in parts of Asia, beyond changes due to land use (*medium confidence*, minor contribution from climate change) [24.3, 24.4, 28.2, Tables 18-5, 18-6, and SM24-4, Box 3-1; WGI AR5 4.3, 10.5]
Terrestrial Ecosystems	• Changes in plant phenology and growth in many parts of Asia (earlier greening), particularly in the north and east (*medium confidence*, major contribution from climate change) • Distribution shifts of many plant and animal species upwards in elevation or polewards, particularly in the north of Asia (*medium confidence*, major contribution from climate change) • Invasion of Siberian larch forests by pine and spruce during recent decades (*low confidence*, major contribution from climate change) • Advance of shrubs into the Siberian tundra (*high confidence*, major contribution from climate change) [4.3, 24.4, 28.2, Table 18-7, Figure 4-4]
Coastal Erosion & Marine Ecosystems	• Decline in coral reefs in tropical Asian waters, beyond decline due to human impacts (*high confidence*, major contribution from climate change) • Northward range extension of corals in the East China Sea and western Pacific, and of a predatory fish in the Sea of Japan (*medium confidence*, major contribution from climate change) • Shift from sardines to anchovies in the western North Pacific, beyond fluctuations due to fisheries (*low confidence*, major contribution from climate change) • Increased coastal erosion in Arctic Asia (*low confidence*, major contribution from climate change) [6.3, 24.4, 30.5, Tables 6-2 and 18-8]
Food Production & Livelihoods	• Impacts on livelihoods of indigenous groups in Arctic Russia, beyond economic and sociopolitical changes (*low confidence*, major contribution from climate change) • Negative impacts on aggregate wheat yields in South Asia, beyond increase due to improved technology (*medium confidence*, minor contribution from climate change) • Negative impacts on aggregate wheat and maize yields in China, beyond increase due to improved technology (*low confidence*, minor contribution from climate change) • Increases in a water-borne disease in Israel (*low confidence*, minor contribution from climate change) [7.2, 13.2, 18.4, 28.2, Tables 18-4 and 18-9, Figure 7-2]
Australasia	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Significant decline in late-season snow depth at 3 of 4 alpine sites in Australia (1957–2002) (*medium confidence*, major contribution from climate change) • Substantial reduction in ice and glacier ice volume in New Zealand (*medium confidence*, major contribution from climate change) • Intensification of hydrological drought due to regional warming in southeast Australia (*low confidence*, minor contribution from climate change) • Reduced inflow in river systems in southwestern Australia (since the mid-1970s) (*high confidence*, major contribution from climate change) [25.5, Tables 18-5, 18-6, and 25-1; WGI AR5 4.3]
Terrestrial Ecosystems	• Changes in genetics, growth, distribution, and phenology of many species, in particular birds, butterflies, and plants in Australia, beyond fluctuations due to variable local climates, land use, pollution, and invasive species (*high confidence*, major contribution from climate change) • Expansion of some wetlands and contraction of adjacent woodlands in southeast Australia (*low confidence*, major contribution from climate change) • Expansion of monsoon rainforest at expense of savannah and grasslands in northern Australia (*medium confidence*, major contribution from climate change) • Migration of glass eels advanced by several weeks in Waikato River, New Zealand (*low confidence*, major contribution from climate change) [Tables 18-7 and 25-3]
Coastal Erosion & Marine Ecosystems	• Southward shifts in the distribution of marine species near Australia, beyond changes due to short-term environmental fluctuations, fishing, and pollution (*medium confidence*, major contribution from climate change) • Change in timing of migration of seabirds in Australia (*low confidence*, major contribution from climate change) • Increased coral bleaching in Great Barrier Reef and western Australian reefs, beyond effects from pollution and physical disturbance (*high confidence*, major contribution from climate change) • Changed coral disease patterns at Great Barrier Reef, beyond effects from pollution (*medium confidence*, major contribution from climate change) [6.3, 25.6, Tables 18-8 and 25-3]
Food Production & Livelihoods	• Advanced timing of wine-grape maturation in recent decades, beyond advance due to improved management (*medium confidence*, major contribution from climate change) • Shift in winter vs. summer human mortality in Australia, beyond changes due to exposure and health care (*low confidence*, major contribution from climate change) • Relocation or diversification of agricultural activities in Australia, beyond changes due to policy, markets, and short-term climate variability (*low confidence*, minor contribution from climate change) [11.4, 18.4, 25.7, 25.8, Tables 18-9 and 25-3, Box 25-5]
North America	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Shrinkage of glaciers across western and northern North America (*high confidence*, major contribution from climate change) • Decreasing amount of water in spring snowpack in western North America (1960–2002) (*high confidence*, major contribution from climate change) • Shift to earlier peak flow in snow dominated rivers in western North America (*high confidence*, major contribution from climate change) • Increased runoff in the midwestern and northeastern US (*medium confidence*, minor contribution from climate change) [Tables 18-5 and 18-6; WGI AR5 2.6, 4.3]
Terrestrial Ecosystems	• Phenology changes and species distribution shifts upward in elevation and northward across multiple taxa (*medium confidence*, major contribution from climate change) • Increased wildfire frequency in subarctic conifer forests and tundra (*medium confidence*, major contribution from climate change) • Regional increases in tree mortality and insect infestations in forests (*low confidence*, minor contribution from climate change) • Increase in wildfire activity, fire frequency and duration, and burnt area in forests of the western US and boreal forests in Canada, beyond changes due to land use and fire management (*medium confidence*, minor contribution from climate change) [26.4, 28.2, Table 18-7, Box 26-2]
Coastal Erosion & Marine Ecosystems	• Northward distributional shifts of northwest Atlantic fish species (*high confidence*, major contribution from climate change) • Changes in musselbeds along the west coast of US (*high confidence*, major contribution from climate change) • Changed migration and survival of salmon in northeast Pacific (*high confidence*, major contribution from climate change) • Increased coastal erosion in Alaska and Canada (*medium confidence*, major contribution from climate change) [18.3, 30.5, Tables 6-2 and 18-8]
Food Production & Livelihoods	• Impacts on livelihoods of indigenous groups in the Canadian Arctic, beyond effects of economic and sociopolitical changes (*medium confidence*, major contribution from climate change) [18.4, 28.2, Tables 18-4 and 18-9]

Continued next page →

Table TS.1 (continued)

Central and South America	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Shrinkage of Andean glaciers (*high confidence*, major contribution from climate change) • Changes in extreme flows in Amazon River (*medium confidence*, major contribution from climate change) • Changing discharge patterns in rivers in the western Andes (*medium confidence*, major contribution from climate change) • Increased streamflow in sub-basins of the La Plata River, beyond increase due to land-use change (*high confidence*, major contribution from climate change) [27.3, Tables 18-5, 18-6, and 27-3; WGI AR5 4.3]
Terrestrial Ecosystems	• Increased tree mortality and forest fire in the Amazon (*low confidence*, minor contribution from climate change) • Rainforest degradation and recession in the Amazon, beyond reference trends in deforestation and land degradation (*low confidence*, minor contribution from climate change) [4.3, 18.3, 27.2, 27.3, Table 18-7]
Coastal Erosion & Marine Ecosystems	• Increased coral bleaching in western Caribbean, beyond effects from pollution and physical disturbance (*high confidence*, major contribution from climate change) • Mangrove degradation on north coast of South America, beyond degradation due to pollution and land use (*low confidence*, minor contribution from climate change) [27.3, Table 18-8]
Food Production & Livelihoods	• More vulnerable livelihood trajectories for indigenous Aymara farmers in Bolivia due to water shortage, beyond effects of increasing social and economic stress (*medium confidence*, major contribution from climate change) • Increase in agricultural yields and expansion of agricultural areas in southeastern South America, beyond increase due to improved technology (*medium confidence*, major contribution from climate change) [13.1, 27.3, Table 18-9]
Polar Regions	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Decreasing Arctic sea ice cover in summer (*high confidence*, major contribution from climate change) • Reduction in ice volume in Arctic glaciers (*high confidence*, major contribution from climate change) • Decreasing snow cover extent across the Arctic (*medium confidence*, major contribution from climate change) • Widespread permafrost degradation, especially in the southern Arctic (*high confidence*, major contribution from climate change) • Ice mass loss along coastal Antarctica (*medium confidence*, major contribution from climate change) • Increased river discharge for large circumpolar rivers (1997–2007) (*low confidence*, major contribution from climate change) • Increased winter minimum river flow in most of the Arctic (*medium confidence*, major contribution from climate change) • Increased lake water temperatures 1985–2009 and prolonged ice-free seasons (*medium confidence*, major contribution from climate change) • Disappearance of thermokarst lakes due to permafrost degradation in the low Arctic. New lakes created in areas of formerly frozen peat (*high confidence*, major contribution from climate change) [28.2, Tables 18-5 and 18-6; WGI AR5 4.2 to 4.4, 4.6, 10.5]
Terrestrial Ecosystems	• Increased shrub cover in tundra in North America and Eurasia (*high confidence*, major contribution from climate change) • Advance of Arctic tree-line in latitude and altitude (*medium confidence*, major contribution from climate change) • Changed breeding area and population size of subarctic birds, due to snowbed reduction and/or tundra shrub encroachment (*medium confidence*, major contribution from climate change) • Loss of snow-bed ecosystems and tussock tundra (*high confidence*, major contribution from climate change) • Impacts on tundra animals from increased ice layers in snow pack, following rain-on-snow events (*medium confidence*, major contribution from climate change) • Increased plant species ranges in the West Antarctic Peninsula and nearby islands over the past 50 years (*high confidence*, major contribution from climate change) • Increased phytoplankton productivity in Signy Island lake waters (*high confidence*, major contribution from climate change) [28.2, Table 18-7]
Coastal Erosion & Marine Ecosystems	• Increased coastal erosion across Arctic (*medium confidence*, major contribution from climate change) • Negative effects on non-migratory Arctic species (*high confidence*, major contribution from climate change) • Decreased reproductive success in Arctic seabirds (*medium confidence*, major contribution from climate change) • Decline in Southern Ocean seals and seabirds (*medium confidence*, major contribution from climate change) • Reduced thickness of foraminiferal shells in southern oceans, due to ocean acidification (*medium confidence*, major contribution from climate change) • Reduced krill density in Scotia Sea (*medium confidence*, major contribution from climate change) [6.3, 18.3, 28.2, 28.3, Table 18-8]
Food Production & Livelihoods	• Impact on livelihoods of Arctic indigenous peoples, beyond effects of economic and sociopolitical changes (*medium confidence*, major contribution from climate change) • Increased shipping traffic across the Bering Strait (*medium confidence*, major contribution from climate change) [18.4, 28.2, Tables 18-4 and 18-9, Figure 28-4]
Small Islands	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Increased water scarcity in Jamaica, beyond increase due to water use (*very low confidence*, minor contribution from climate change) [Table 18-6]
Terrestrial Ecosystems	• Tropical bird population changes in Mauritius (*medium confidence*, major contribution from climate change) • Decline of an endemic plant in Hawai'i (*medium confidence*, major contribution from climate change) • Upward trend in tree-lines and associated fauna on high-elevation islands (*low confidence*, minor contribution from climate change) [29.3, Table 18-7]
Coastal Erosion & Marine Ecosystems	• Increased coral bleaching near many tropical small islands, beyond effects of degradation due to fishing and pollution (*high confidence*, major contribution from climate change) • Degradation of mangroves, wetlands, and seagrass around small islands, beyond degradation due to other disturbances (*very low confidence*, minor contribution from climate change) • Increased flooding and erosion, beyond erosion due to human activities, natural erosion, and accretion (*low confidence*, minor contribution from climate change) • Degradation of groundwater and freshwater ecosystems due to saline intrusion, beyond degradation due to pollution and groundwater pumping (*low confidence*, minor contribution from climate change) [29.3, Table 18-8]
Food Production & Livelihoods	• Increased degradation of coastal fisheries due to direct effects and effects of increased coral reef bleaching, beyond degradation due to overfishing and pollution (*low confidence*, minor contribution from climate change) [18.3, 18.4, 29.3, 30.6, Table 18-9, Box CC-CR]

species extinctions have not been attributed to climate change (*high confidence*). [4.2, 4.4, 18.3, 18.5, 22.3, 25.6, 26.4, 28.2, Figure 4-10, Boxes 4-2, 4-3, 4-4, and 25-3]

Coastal Systems and Low-lying Areas

Coastal systems are particularly sensitive to changes in sea level and ocean temperature and to ocean acidification (*very high confidence*). Coral bleaching and species range shifts have been attributed to changes in ocean temperature. For many other coastal changes, the impacts of climate change are difficult to identify given other human-related drivers (e.g. land use change, coastal development, pollution) (*robust evidence*, *high agreement*). [5.3 to 5.5, 18.3, 25.6, 26.4, Box 25-3]

Marine Systems

Warming has caused and will continue to cause shifts in the abundance, geographic distribution, migration patterns, and timing of seasonal activities of marine species (*very high confidence*), paralleled by reduction in maximum body sizes (*medium confidence*). This has resulted and will further result in changing interactions between species, including competition and predator-prey dynamics (*high confidence*). Numerous observations over the last decades in all ocean basins show global-scale changes including large-scale distribution shifts of species (*very high confidence*) and altered ecosystem composition (*high confidence*) on multi-decadal time scales, tracking climate trends. Many fishes, invertebrates, and phytoplankton have shifted their distribution and/or abundance poleward and/or to deeper, cooler waters (Figure TS.2D). Some warm-water corals and their reefs have responded to warming with species replacement, bleaching, and decreased coral cover causing habitat loss. Few field observations to date demonstrate biological responses attributable to anthropogenic ocean acidification, as in many places these responses are not yet outside their natural variability and may be influenced by confounding local or regional factors. See also Box TS.7. Natural global climate change at rates slower than current anthropogenic climate change caused significant ecosystem shifts, including species emergences and extinctions, during the past millions of years. [5.4, 6.1, 6.3 to 6.5, 18.3, 18.5, 22.3, 25.6, 26.4, 30.4, 30.5, Boxes 25-3, CC-OA, CC-CR, and CC-MB]

Vulnerability of most marine organisms to warming is set by their physiology, which defines their limited temperature ranges and hence their thermal sensitivity (*high confidence*). See Figure TS.3. Temperature defines the geographic distribution of many species and their responses to climate change. Shifting temperature means and extremes alter habitat (e.g., sea ice and coastal habitat), and cause changes in species abundances through local extinctions and latitudinal distribution expansions or shifts of up to hundreds of kilometers per decade (*very high confidence*). Although genetic adaptation occurs (*medium confidence*), the capacity of fauna and flora to compensate for or keep up with the rate of ongoing thermal change is limited (*low confidence*). [6.3, 6.5, 30.5]

Oxygen minimum zones are progressively expanding in the tropical Pacific, Atlantic, and Indian Oceans, due to reduced ventilation and O_2 solubilities in more stratified oceans at higher temperatures (*high confidence*). In combination with human activities that increase the productivity of coastal systems, hypoxic areas ("dead zones") are increasing in number and size. Regional exacerbation of hypoxia causes shifts to hypoxia-tolerant biota and reduces habitat for commercially relevant species, with implications for fisheries. [6.1, 6.3, 30.3, 30.5, 30.6; WGI AR5 3.8]

Food Security and Food Production Systems

Based on many studies covering a wide range of regions and crops, negative impacts of climate change on crop yields have been more common than positive impacts (*high confidence*). The smaller number of studies showing positive impacts relate mainly to high-latitude regions, though it is not yet clear whether the balance of impacts has been negative or positive in these regions. Climate change has negatively affected wheat and maize yields for many regions and in the global aggregate (*medium confidence*). Effects on rice and soybean yield have been smaller in major production regions and globally, with a median change of zero across all available data, which are fewer for soy compared to the other crops. Observed impacts relate mainly to production aspects of food security rather than access or other components of food security. See Figure TS.2E. Since AR4, several periods of rapid food and cereal price increases following climate extremes in key producing regions indicate a sensitivity of current markets to climate extremes among other factors (*medium confidence*). Crop yields have a large negative sensitivity to extreme daytime temperatures around 30°C, throughout the growing season (*high confidence*). CO_2 has stimulatory effects on crop yields in most cases, and elevated tropospheric ozone has damaging effects. Interactions among CO_2 and ozone, mean temperature, extremes, water, and nitrogen are non-linear and difficult to predict (*medium confidence*). [7.2, 7.3, 18.4, 22.3, 26.5, Figures 7-2, 7-3, and 7-7, Box 25-3]

Urban Areas

Urban areas hold more than half the world's population and most of its built assets and economic activities. A high proportion of the population and economic activities at risk from climate change are in urban areas, and a high proportion of global greenhouse gas emissions are generated by urban-based activities and residents. Cities are composed of complex inter-dependent systems that can be leveraged to support climate change adaptation via effective city governments supported by cooperative multilevel governance (*medium confidence*). This can enable synergies with infrastructure investment and maintenance, land use management, livelihood creation, and ecosystem services protection. [8.1, 8.3, 8.4]

Rapid urbanization and growth of large cities in developing countries have been accompanied by expansion of highly vulnerable urban communities living in informal settlements, many of which are on land exposed to extreme weather (*medium confidence*). [8.2, 8.3]

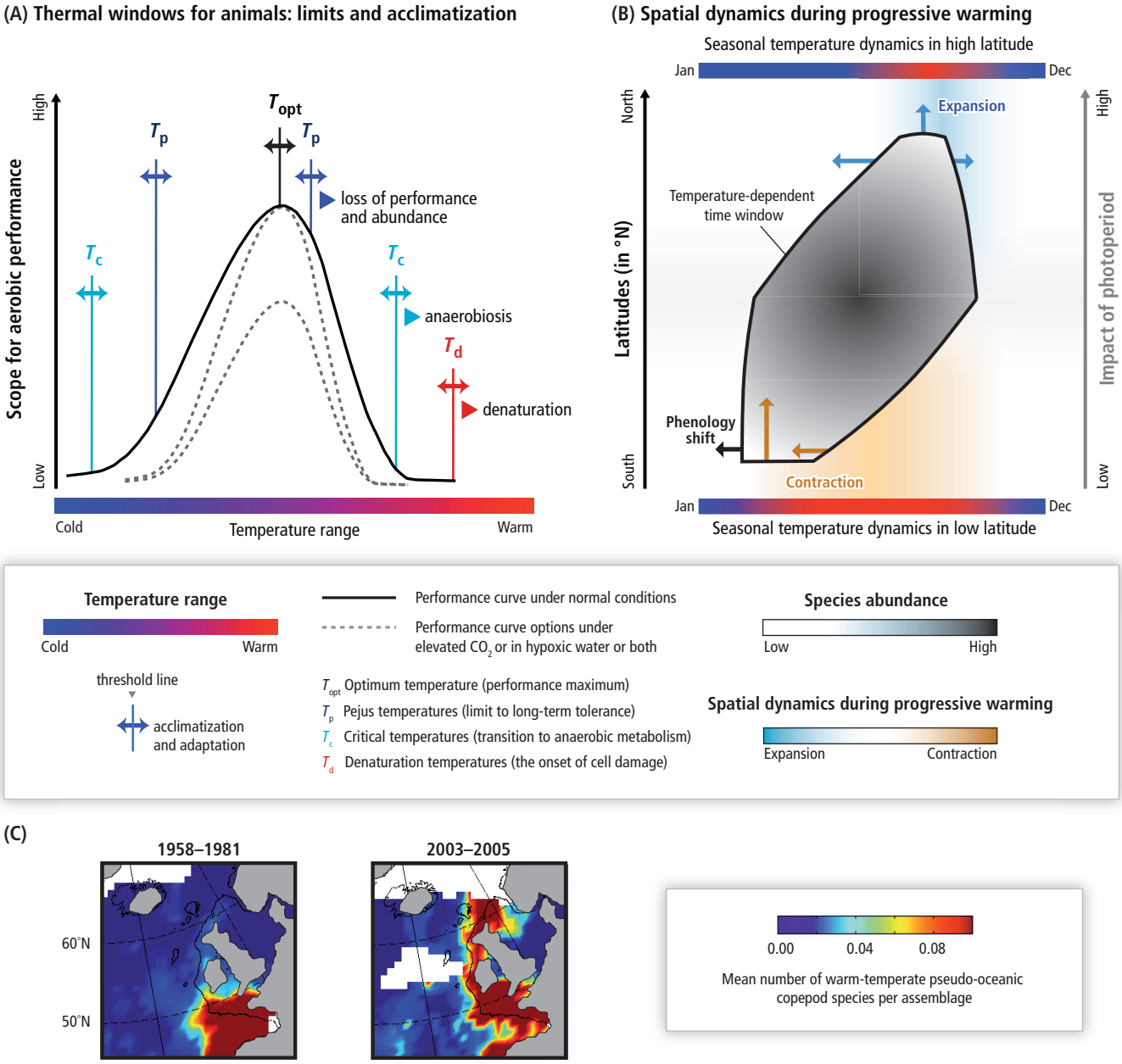


Figure TS.3 | Temperature specialization of species (A), which is influenced by other factors such as oxygen, causes warming-induced distribution shifts (B), for example, the northward expansion of warm-temperate species in the northeast Atlantic (C). These distribution changes depend on species-specific physiology and ecology. Detailed introduction of each panel follows: (A) The temperature tolerance range and performance levels of an organism are described by its performance curve. Each performance (e.g., exercise, growth, reproduction) is highest at optimum temperature (T_{opt}) and lower at cooler or warmer temperatures. Surpassing temperature thresholds (T_p) means going into time-limited tolerance, and more extreme temperature changes lead to exceedance of thresholds that cause metabolic disturbances (T_c) and ultimately onset of cell damage (T_d). These thresholds for an individual can shift (horizontal arrows), within limits, between summer and winter (seasonal acclimatization) or when the species adapts to a cooler or warmer climate over generations (evolutionary adaptation). Under elevated CO_2 levels (ocean acidification) or low oxygen, thermal windows narrow (dashed gray curves). (B) During climate warming, a species follows its normal temperatures as it moves or is displaced, typically resulting in a poleward shift of the biogeographic range (exemplified for the Northern Hemisphere). The polygon delineates the distribution range in space and seasonal time; the level of gray denotes abundance. (C) Long-term changes in the mean number of warm-temperate pseudo-oceanic copepod species in the northeast Atlantic from 1958 to 2005. [Figures 6-5, 6-7, and 6-8]

Rural Areas

Climate change in rural areas will take place in the context of many important economic, social, and land use trends (*very high confidence*). In different regions, absolute rural populations have peaked or will peak in the next few decades. The proportion of the rural population depending on agriculture is varied across regions, but declining everywhere. Poverty rates in rural areas are higher than overall poverty rates, but also falling more sharply, and the proportions of population in extreme poverty accounted for by rural people are also falling: in both cases with the exception of sub-Saharan Africa, where these rates are rising. Accelerating globalization, through migration,

labor linkages, regional and international trade, and new information and communication technologies, is bringing about economic transformation in rural areas of developing and developed countries. [9.3, Figure 9-2]

For rural households and communities, access to land and natural resources, flexible local institutions, knowledge and information, and livelihood strategies can contribute to resilience to climate change (*high confidence*). Especially in developing countries, rural people are subject to multiple non-climatic stressors, including underinvestment in agriculture, problems with land and natural resource policy, and processes of environmental degradation (*very high confidence*). In developed countries, there are important shifts toward multiple uses of rural areas, especially leisure uses, and new rural policies based on the collaboration of multiple stakeholders, the targeting of multiple sectors, and a change from subsidy-based to investment-based policy. [9.3, 22.4, Table 9-3]

Key Economic Sectors and Services

Economic losses due to extreme weather events have increased globally, mostly due to increase in wealth and exposure, with a possible influence of climate change (*low confidence* in attribution to climate change). Flooding can have major economic costs, both in term of impacts (e.g., capital destruction, disruption) and adaptation (e.g., construction, defensive investment) (*robust evidence*, *high agreement*). Since the mid-20th century, socioeconomic losses from flooding have increased mainly due to greater exposure and vulnerability (*high confidence*). [3.2, 3.4, 10.3, 18.4, 23.2, 23.3, 26.7, Figure 26-2, Box 25-7]

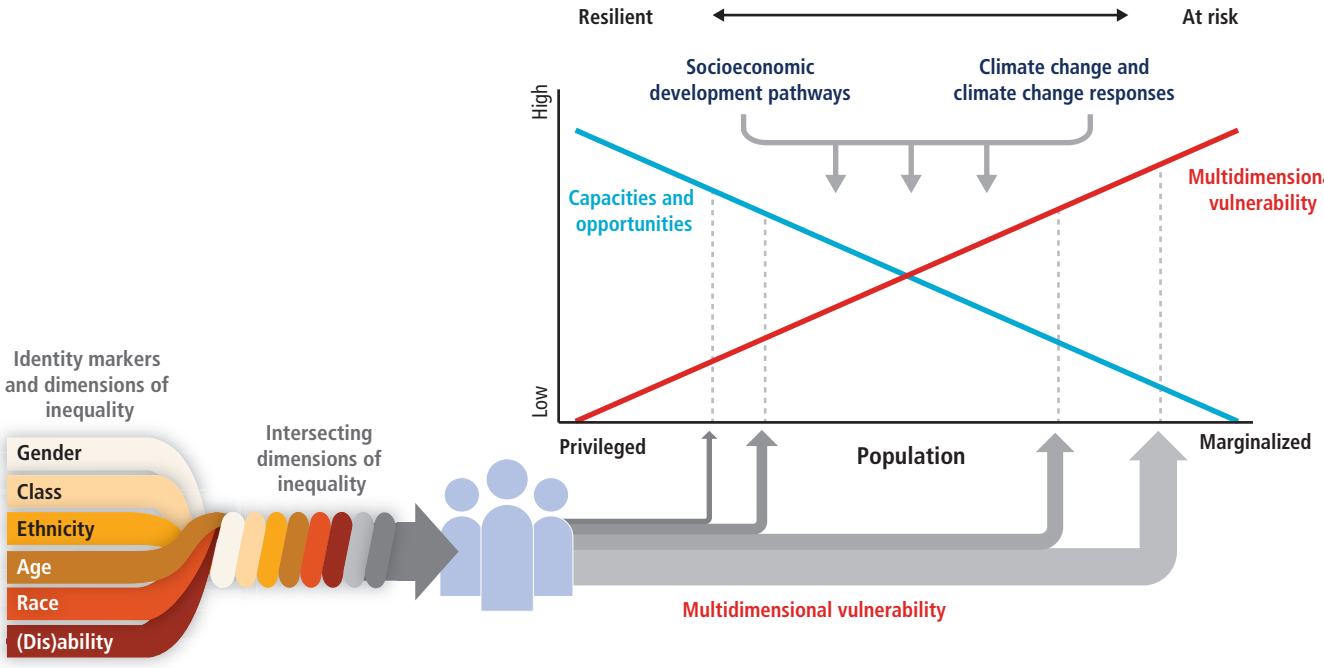
Human Health

At present the worldwide burden of human ill-health from climate change is relatively small compared with effects of other stressors and is not well quantified. However, there has been increased heat-related mortality and decreased cold-related mortality in some regions as a result of warming (*medium confidence*). Local changes in temperature and rainfall have altered the distribution of some waterborne illnesses and disease vectors (*medium confidence*). [11.4 to 11.6, 18.4, 25.8]

The health of human populations is sensitive to shifts in weather patterns and other aspects of climate change (*very high confidence*). These effects occur directly, due to changes in temperature and precipitation and in the occurrence of heat waves, floods, droughts, and fires. Health may be damaged indirectly by climate change-related ecological disruptions, such as crop failures or shifting patterns of disease vectors, or by social responses to climate change, such as displacement of populations following prolonged drought. Variability in temperatures is a risk factor in its own right, over and above the influence of average temperatures on heat-related deaths. [11.4, 28.2]

Human Security

Challenges for vulnerability reduction and adaptation actions are particularly high in regions that have shown severe difficulties in governance (*high confidence*). Violent conflict increases vulnerability to climate change (*medium evidence*, *high agreement*). Large-scale violent conflict harms assets that facilitate adaptation, including infrastructure, institutions, natural resources, social capital, and livelihood opportunities. [12.5, 19.2, 19.6]



Box TS.4 Figure 1 | Multidimensional vulnerability driven by intersecting dimensions of inequality. Vulnerability increases when people's capacities and opportunities to adapt to climate change and adjust to climate change responses are diminished. [Figure 13-5]

Box TS.4 | Multidimensional Inequality and Vulnerability to Climate Change

People who are socially, economically, culturally, politically, institutionally, or otherwise marginalized in society are especially vulnerable to climate change and also to some adaptation and mitigation responses (*medium evidence*, *high agreement*). This heightened vulnerability is rarely due to a single cause. Rather, it is the product of intersecting social processes that result in inequalities in socioeconomic status and income, as well as in exposure. Such social processes include, for example, discrimination on the basis of gender, class, race/ethnicity, age, and (dis)ability. See Box TS.4 Figure 1 on previous page. Understanding differential capacities and opportunities of individuals, households, and communities requires knowledge of these intersecting social drivers, which may be context-specific and clustered in diverse ways (e.g., class and ethnicity in one case, gender and age in another). Few studies depict the full spectrum of these intersecting social processes and the ways in which they shape multidimensional vulnerability to climate change.

Examples of inequality-driven impacts and risks of climate change and climate change responses (*medium evidence*, *high agreement*):

- Privileged members of society can benefit from climate change impacts and response strategies, given their flexibility in mobilizing and accessing resources and positions of power, often to the detriment of others. [13.2, 13.3, 22.4, 26.8]
- Differential impacts on men and women arise from distinct roles in society, the way these roles are enhanced or constrained by other dimensions of inequality, risk perceptions, and the nature of response to hazards. [8.2, 9.3, 11.3, 12.2, 13.2, 18.4, 19.6, 22.4, Box CC-GC]
- Both male and female deaths are recorded after flooding, affected by socioeconomic disadvantage, occupation, and culturally imposed expectations to save lives. Although women are generally more sensitive to heat stress, more male workers are reported to have died largely as a result of responsibilities related to outdoor and indoor work. [11.3, 13.2, Box CC-GC]
- Women often experience additional duties as laborers and caregivers as a result of extreme weather events and climate change, as well as responses (e.g., male outmigration), while facing more psychological and emotional distress, reduced food intake, adverse mental health outcomes due to displacement, and in some cases increasing incidences of domestic violence. [9.3, 9.4, 12.4, 13.2, Box CC-GC]
- Children and the elderly are often at higher risk due to narrow mobility, susceptibility to infectious diseases, reduced caloric intake, and social isolation. While adults and older children are more severely affected by some climate-sensitive vector-borne diseases such as dengue, young children are more likely to die from or be severely compromised by diarrheal diseases and floods. The elderly face disproportional physical harm and death from heat stress, droughts, and wildfires. [8.2, 10.9, 11.1, 11.4, 11.5, 13.2, 22.4, 23.5, 26.6]
- In most urban areas, low-income groups, including migrants, face large climate change risks because of poor-quality, insecure, and clustered housing, inadequate infrastructure, and lack of provision for health care, emergency services, flood exposure, and measures for disaster risk reduction. [8.1, 8.2, 8.4, 8.5, 12.4, 22.3, 26.8]
- People disadvantaged by race or ethnicity, especially in developed countries, experience more harm from heat stress, often due to low economic status and poor health conditions, and displacement after extreme events. [11.3, 12.4, 13.2]
- Livelihoods and lifestyles of indigenous peoples, pastoralists, and fisherfolk, often dependent on natural resources, are highly sensitive to climate change and climate change policies, especially those that marginalize their knowledge, values, and activities. [9.3, 11.3, 12.3, 14.2, 22.4, 25.8, 26.8, 28.2]
- Disadvantaged groups without access to land and labor, including female-headed households, tend to benefit less from climate change response mechanisms (e.g., Clean Development Mechanism (CDM), Reduction of Emissions from Deforestation and Forest Degradation (REDD+), large-scale land acquisition for biofuels, and planned agricultural adaptation projects). [9.3, 12.2, 12.5, 13.3, 22.4, 22.6]

Livelihoods and Poverty

Climate-related hazards exacerbate other stressors, often with negative outcomes for livelihoods, especially for people living in poverty (*high confidence*). Climate-related hazards affect poor people's lives directly through impacts on livelihoods, reductions in crop yields, or destruction of homes and indirectly through, for example, increased food prices and food insecurity. Urban and rural transient poor who face multiple deprivations can slide into chronic poverty as a result of extreme events, or a series of events, when unable to rebuild their eroded assets (*limited evidence*, *high agreement*). Observed positive effects for poor and marginalized people, which are limited and often indirect, include examples such as diversification of social networks and of agricultural practices. [8.2, 8.3, 9.3, 11.3, 13.1 to 13.3, 22.3, 24.4, 26.8]

Livelihoods of indigenous peoples in the Arctic have been altered by climate change, through impacts on food security and traditional and cultural values (*medium confidence*). There is emerging evidence of climate change impacts on livelihoods of indigenous people in other regions. [18.4, Table 18-9, Box 18-5]

A-2. Adaptation Experience

Throughout history, people and societies have adjusted to and coped with climate, climate variability, and extremes, with varying degrees of success. This section focuses on adaptive human responses to observed and projected climate-change impacts, which can also address broader risk-reduction and development objectives.

Adaptation is becoming embedded in some planning processes, with more limited implementation of responses (*high confidence*). Engineered and technological options are commonly implemented adaptive responses, often integrated within existing programs such as disaster risk management and water management. There is increasing recognition of the value of social, institutional, and ecosystem-based measures and of the extent of constraints to adaptation. Adaptation options adopted to date continue to emphasize incremental adjustments and co-benefits and are starting to emphasize flexibility and learning (*medium evidence*, *medium agreement*). [4.4, 5.5, 6.4, 8.3, 9.4, 11.7, 14.1, 14.3, 15.2 to 15.5, 17.2, 17.3, 22.4, 23.7, 25.4, 25.10, 26.8, 26.9, 27.3, 30.6, Boxes 25-1, 25-2, 25-9, and CC-EA]

Most assessments of adaptation have been restricted to impacts, vulnerability, and adaptation planning, with very few assessing the processes of implementation or the effects of adaptation actions (*medium evidence*, *high agreement*). Vulnerability indicators define, quantify, and weight aspects of vulnerability across regional units, but methods of constructing indices are subjective, often lack transparency, and can be difficult to interpret. There are conflicting views on the choice of adaptation metrics, given differing values placed on needs and outcomes, many of which cannot be captured in a comparable way by metrics. Indicators proving most useful for policy learning are those that track not just process and implementation, but also the extent to which targeted outcomes are occurring. Multi-metric evaluations including risk and uncertainty are increasingly used, an evolution from a previous focus on cost-benefit analysis and identification of "best economic adaptations" (*high confidence*). Adaptation assessments best suited to delivering effective adaptation measures often include both top-down assessments of biophysical climate changes and bottom-up assessments of vulnerability targeted toward local solutions to globally derived risks and toward particular decisions. [4.4, 14.4, 14.5, 15.2, 15.3, 17.2, 17.3, 21.3, 21.5, 22.4, 25.4, 25.10, 26.8, 26.9, Box CC-EA]

Adaptation experience is accumulating across regions in the public and private sector and within communities (*high confidence*). Governments at various levels are starting to develop adaptation plans and policies and to integrate climate-change considerations into broader development plans. Examples of adaptation across regions and contexts include the following:

- Urban adaptation has emphasized city-based disaster risk management such as early warning systems and infrastructure investments; ecosystem-based adaptation and green roofs; enhanced storm and wastewater management; urban and peri-urban agriculture improving food security; enhanced social protection; and good-quality, affordable, and well-located housing (*high confidence*). [8.3, 8.4, 15.4, 26.8, Boxes 25-9, CC-UR, and CC-EA]
- There is a growing body of literature on adaptation practices in both developed and developing country rural areas, including documentation of practical experience in agriculture, water, forestry, and biodiversity and, to a lesser extent, fisheries (*very high confidence*). Public policies supporting decision making for adaptation in rural areas exist in developed and, increasingly, developing countries, and there are also examples of private adaptations led by individuals, companies, and nongovernmental organizations (NGOs) (*high confidence*). Adaptation constraints, particularly pronounced in developing countries, result from lack of access to credit, land, water, technology, markets, information, and perceptions of the need to change. [9.4, 17.3, Tables 9-7 and 9-8]
- In Africa, most national governments are initiating governance systems for adaptation (*high confidence*). Progress on national and subnational policies and strategies has initiated the mainstreaming of adaptation into sectoral planning, but evolving institutional frameworks cannot yet effectively coordinate the range of adaptation initiatives being implemented. Disaster risk management, adjustments in technologies and infrastructure, ecosystem-based approaches, basic public health measures, and livelihood diversification are reducing vulnerability, although efforts to date tend to be isolated. [22.4]
- In Europe, adaptation policy has been developed at international (EU), national, and local government levels, with limited systematic information on current implementation or effectiveness (*high confidence*). Some adaptation planning has been integrated into coastal and water management, into environmental protection and land planning, and into disaster risk management. [23.7, Boxes 5-1 and 23-3]
- In Asia, adaptation is being facilitated in some areas through mainstreaming climate adaptation action into subnational development planning, early warning systems, integrated water resources management, agroforestry, and coastal reforestation of mangroves (*high confidence*). [24.4 to 24.6, 24.9, Box CC-TC]
- In Australasia, planning for sea level rise, and in southern Australia for reduced water availability, is becoming adopted widely. Planning

Table TS.2 | Illustrative examples of adaptation experience, as well as approaches to reducing vulnerability and enhancing resilience. Adaptation actions can be influenced by climate variability, extremes, and change, and by exposure and vulnerability at the scale of risk management. Many examples and case studies demonstrate complexity at the level of communities or specific regions within a country. It is at this spatial scale that complex interactions between vulnerability, exposure, and climate change come to the fore. [Table 21-4]

Early warning systems for heat	
Exposure and vulnerability	Factors affecting exposure and vulnerability include age, preexisting health status, level of outdoor activity, socioeconomic factors including poverty and social isolation, access to and use of cooling, physiological and behavioral adaptation of the population, urban heat island effects, and urban infrastructure. [8.2.3, 8.2.4, 11.3.3, 11.3.4, 11.4.1, 11.7, 13.2.1, 19.3.2, 23.5.1, 25.3, 25.8.1, SREX Table SPM.1]
Climate information at the global scale	**Observed:** • *Very likely* decrease in the number of cold days and nights and increase in the number of warm days and nights, on the global scale between 1951 and 2010. [WGI AR5 2.6.1] • *Medium confidence* that the length and frequency of warm spells, including heat waves, has increased globally since 1950. [WGI AR5 2.6.1] **Projected:** *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global mean temperatures increase, for events defined as extremes on both daily and seasonal time scales. [WGI AR5 12.4.3]
Climate information at the regional scale	**Observed:** • *Likely* that heat wave frequency has increased since 1950 in large parts of Europe, Asia, and Australia. [WGI AR5 2.6.1] • *Medium confidence* in overall increase in heat waves and warm spells in North America since 1960. Insufficient evidence for assessment or spatially varying trends in heat waves or warm spells for South America and most of Africa. [SREX Table 3-2; WGI AR5 2.6.1] **Projected:** • *Likely* that, by the end of the 21st century under Representative Concentration Pathway 8.5 (RCP8.5) in most land regions, a current 20-year high-temperature event will at least double its frequency and in many regions occur every 2 years or annually, while a current 20-year low-temperature event will become exceedingly rare. [WGI AR5 12.4.3] • *Very likely* more frequent and/or longer heat waves or warm spells over most land areas. [WGI AR5 12.4.3]
Description	Heat-health early warning systems are instruments to prevent negative health impacts during heat waves. Weather forecasts are used to predict situations associated with increased mortality or morbidity. Components of effective heat wave and health warning systems include identifying weather situations that adversely affect human health, monitoring weather forecasts, communicating heat wave and prevention responses, targeting notifications to vulnerable populations, and evaluating and revising the system to increase effectiveness in a changing climate. Warning systems for heat waves have been planned and implemented broadly, for example in Europe, the United States, Asia, and Australia. [11.7.3, 24.4.6, 25.8.1, 26.6, Box 25-6]
Broader context	• Heat-health warning systems can be combined with other elements of a health protection plan, for example building capacity to support communities most at risk, supporting and funding health services, and distributing public health information. • In Africa, Asia, and elsewhere, early warning systems have been used to provide warning of and reduce a variety of risks related to famine and food insecurity; flooding and other weather-related hazards; exposure to air pollution from fire; and vector-borne and food-borne disease outbreaks. [7.5.1, 11.7, 15.4.2, 22.4.5, 24.4.6, 25.8.1, 26.6.3, Box 25-6]
Mangrove restoration to reduce flood risks and protect shorelines from storm surge	
Exposure and vulnerability	Loss of mangroves increases exposure of coastlines to storm surge, coastal erosion, saline intrusion, and tropical cyclones. Exposed infrastructure, livelihoods, and people are vulnerable to associated damage. Areas with development in the coastal zone, such as on small islands, can be particularly vulnerable. [5.4.3, 5.5.6, 29.7.2, Box CC-EA]
Climate information at the global scale	**Observed:** • *Likely* increase in the magnitude of extreme high sea level events since 1970, mostly explained by rising mean sea level. [WGI AR5 3.7.5] • *Low confidence* in long-term (centennial) changes in tropical cyclone activity, after accounting for past changes in observing capabilities. [WGI AR5 2.6.3] **Projected:** • *Very likely* significant increase in the occurrence of future sea level extremes by 2050 and 2100. [WGI AR5 13.7.2] • In the 21st century, *likely* that the global frequency of tropical cyclones will either decrease or remain essentially unchanged. *Likely* increase in both global mean tropical cyclone maximum wind speed and rainfall rates. [WGI AR5 14.6]
Climate information at the regional scale	**Observed:** Change in sea level relative to the land (relative sea level) can be significantly different from the global mean sea level change because of changes in the distribution of water in the ocean and vertical movement of the land. [WGI AR5 3.7.3] **Projected:** • *Low confidence* in region-specific projections of storminess and associated storm surges. [WGI AR5 13.7.2] • Projections of regional changes in sea level reach values of up to 30% above the global mean value in the Southern Ocean and around North America, and between 10% to 20% above the global mean value in equatorial regions. [WGI AR5 13.6.5] • *More likely than not* substantial increase in the frequency of the most intense tropical cyclones in the western North Pacific and North Atlantic. [WGI AR5 14.6]
Description	Mangrove restoration and rehabilitation has occurred in a number of locations (e.g., Vietnam, Djibouti, and Brazil) to reduce coastal flooding risks and protect shorelines from storm surge. Restored mangroves have been shown to attenuate wave height and thus reduce wave damage and erosion. They protect aquaculture industry from storm damage and reduce saltwater intrusion. [2.4.3, 5.5.4, 8.3.3, 22.4.5, 27.3.3]
Broader context	• Considered a low-regrets option benefiting sustainable development, livelihood improvement, and human well-being through improvements for food security and reduced risks from flooding, saline intrusion, wave damage, and erosion. Restoration and rehabilitation of mangroves, as well as of wetlands or deltas, is ecosystem-based adaptation that enhances ecosystem services. • Synergies with mitigation given that mangrove forests represent large stores of carbon. • Well-integrated ecosystem-based adaptation can be more cost effective and sustainable than non-integrated physical engineering approaches. [5.5, 8.4.2, 14.3.1, 24.6, 29.3.1, 29.7.2, 30.6.1, 30.6.2, Table 5-4, Box CC-EA]

Continued next page →

Table TS.2 (continued)

Community-based adaptation and traditional practices in small island contexts	
Exposure and vulnerability	With small land area, often low elevation coasts, and concentration of human communities and infrastructure in coastal zones, small islands are particularly vulnerable to rising sea levels and impacts such as inundation, saltwater intrusion, and shoreline change. [29.3.1, 29.3.3, 29.6.1, 29.6.2, 29.7.2]
Climate information at the global scale	**Observed:** • *Likely* increase in the magnitude of extreme high sea level events since 1970, mostly explained by rising mean sea level. [WGI AR5 3.7.5] • *Low confidence* in long-term (centennial) changes in tropical cyclone activity, after accounting for past changes in observing capabilities. [WGI AR5 2.6.3] • Since 1950 the number of heavy precipitation events over land has *likely* increased in more regions than it has decreased. [WGI AR5 2.6.2] **Projected:** • *Very likely* significant increase in the occurrence of future sea level extremes by 2050 and 2100. [WGI AR5 13.7.2] • In the 21st century, *likely* that the global frequency of tropical cyclones will either decrease or remain essentially unchanged. *Likely* increase in both global mean tropical cyclone maximum wind speed and rainfall rates. [WGI AR5 14.6] • Globally, for short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 12.4.5]
Climate information at the regional scale	**Observed:** Change in sea level relative to the land (relative sea level) can be significantly different from the global mean sea level change because of changes in the distribution of water in the ocean and vertical movement of the land. [WGI AR5 3.7.3] **Projected:** • *Low confidence* in region-specific projections of storminess and associated storm surges. [WGI AR5 13.7.2] • Projections of regional changes in sea level reach values of up to 30% above the global mean value in the Southern Ocean and around North America, and between 10% and 20% above the global mean value in equatorial regions. [WGI AR5 13.6.5] • *More likely than not* substantial increase in the frequency of the most intense tropical cyclones in the western North Pacific and North Atlantic. [WGI AR5 14.6]
Description	Traditional technologies and skills can be relevant for climate adaptation in small island contexts. In the Solomon Islands, relevant traditional practices include elevating concrete floors to keep them dry during heavy precipitation events and building low aerodynamic houses with palm leaves as roofing to avoid hazards from flying debris during cyclones, supported by perceptions that traditional construction methods are more resilient to extreme weather. In Fiji after Cyclone Ami in 2003, mutual support and risk sharing formed a central pillar for community-based adaptation, with unaffected households fishing to support those with damaged homes. Participatory consultations across stakeholders and sectors within communities and capacity building taking into account traditional practices can be vital to the success of adaptation initiatives in island communities, such as in Fiji or Samoa. [29.6.2]
Broader context	• Perceptions of self-efficacy and adaptive capacity in addressing climate stress can be important in determining resilience and identifying useful solutions. • The relevance of community-based adaptation principles to island communities, as a facilitating factor in adaptation planning and implementation, has been highlighted, for example, with focus on empowerment and learning-by-doing, while addressing local priorities and building on local knowledge and capacity. Community-based adaptation can include measures that cut across sectors and technological, social, and institutional processes, recognizing that technology by itself is only one component of successful adaptation. [5.5.4, 29.6.2]
Adaptive approaches to flood defense in Europe	
Exposure and vulnerability	Increased exposure of persons and property in flood risk areas has contributed to increased damages from flood events over recent decades. [5.4.3, 5.4.4, 5.5.5, 23.3.1, Box 5-1]
Climate information at the global scale	**Observed:** • *Likely* increase in the magnitude of extreme high sea level events since 1970, mostly explained by rising mean sea level. [WGI AR5 3.7.5] • Since 1950 the number of heavy precipitation events over land has *likely* increased in more regions than it has decreased. [WGI AR5 2.6.2] **Projected:** • *Very likely* that the time-mean rate of global mean sea level rise during the 21st century will exceed the rate observed during 1971–2010 for all RCP scenarios. [WGI AR5 13.5.1] • Globally, for short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 12.4.5]
Climate information at the regional scale	**Observed:** • *Likely* increase in the frequency or intensity of heavy precipitation in Europe, with some seasonal and/or regional variations. [WGI AR5 2.6.2] • Increase in heavy precipitation in winter since the 1950s in some areas of northern Europe (*medium confidence*). Increase in heavy precipitation since the 1950s in some parts of west-central Europe and European Russia, especially in winter (*medium confidence*). [SREX Table 3-2] • Increasing mean sea level with regional variations, except in the Baltic Sea where the relative sea level is decreasing due to vertical crustal motion. [5.3.2, 23.2.2] **Projected:** • Over most of the mid-latitude land masses, extreme precipitation events will *very likely* be more intense and more frequent in a warmer world. [WGI AR5 12.4.5] • Overall precipitation increase in northern Europe and decrease in southern Europe (*medium confidence*). [23.2.2] • Increased extreme precipitation in northern Europe during all seasons, particularly winter, and in central Europe except in summer (*high confidence*). [23.2.2; SREX Table 3-3]
Description	Several governments have made ambitious efforts to address flood risk and sea level rise over the coming century. In the Netherlands, government recommendations include "soft" measures preserving land from development to accommodate increased river inundation; maintaining coastal protection through beach nourishment; and ensuring necessary political-administrative, legal, and financial resources. Through a multi-stage process, the British government has also developed extensive adaptation plans to adjust and improve flood defenses to protect London from future storm surges and river flooding. Pathways have been analyzed for different adaptation options and decisions, depending on eventual sea level rise, with ongoing monitoring of the drivers of risk informing decisions. [5.5.4, 23.7.1, Box 5-1]
Broader context	• The Dutch plan is considered a paradigm shift, addressing coastal protection by "working with nature" and providing "room for river." • The British plan incorporates iterative, adaptive decisions depending on the eventual sea level rise with numerous and diverse measures possible over the next 50 to 100 years to reduce risk to acceptable levels. • In cities in Europe and elsewhere, the importance of strong political leadership or government champions in driving successful adaptation action has been noted. [5.5.3, 5.5.4, 8.4.3, 23.7.1, 23.7.2, 23.7.4, Boxes 5-1 and 26-3]

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Table TS.2 (continued)

Index-based insurance for agriculture in Africa	
Exposure and vulnerability	Susceptibility to food insecurity and depletion of farmers' productive assets following crop failure. Low prevalence of insurance due to absent or poorly developed insurance markets or to amount of premium payments. The most marginalized and resource-poor especially may have limited ability to afford insurance premiums. [10.7.6, 13.3.2, Box 22-1]
Climate information at the global scale	**Observed:** • *Very likely* decrease in the number of cold days and nights and increase in the number of warm days and nights, on the global scale between 1951 and 2010. [WGI AR5 2.6.1] • *Medium confidence* that the length and frequency of warm spells, including heat waves, has increased globally since 1950. [WGI AR5 2.6.1] • Since 1950 the number of heavy precipitation events over land has *likely* increased in more regions than it has decreased. [WGI AR5 2.6.2] • *Low confidence* in a global-scale observed trend in drought or dryness (lack of rainfall). [WGI AR5 2.6.2] **Projected:** • *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global mean temperatures increase, for events defined as extremes on both daily and seasonal time scales. [WGI AR5 12.4.3] • Regional to global-scale projected decreases in soil moisture and increased risk of agricultural drought are *likely* in presently dry regions, and are projected with *medium confidence* by the end of this century under the RCP8.5 scenario. [WGI AR5 12.4.5] • Globally, for short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 12.4.5]
Climate information at the regional scale	**Observed:** • *Medium confidence* in increase in frequency of warm days and decrease in frequency of cold days and nights in southern Africa. [SREX Table 3-2] • *Medium confidence* in increase in frequency of warm nights in northern and southern Africa. [SREX Table 3-2] **Projected:** • *Likely* surface drying in southern Africa by the end of the 21st century under RCP8.5 (*high confidence*). [WGI AR5 12.4.5] • *Likely* increase in warm days and nights and decrease in cold days and nights in all regions of Africa (*high confidence*). Increase in warm days largest in summer and fall (*medium confidence*). [SREX Table 3-3] • *Likely* more frequent and/or longer heat waves and warm spells in Africa (*high confidence*). [SREX Table 3-3]
Description	A recently introduced mechanism that has been piloted in a number of rural locations, including in Malawi, Sudan, and Ethiopia, as well as in India. When physical conditions reach a particular predetermined threshold where significant losses are expected to occur—weather conditions such as excessively high or low cumulative rainfall or temperature peaks—the insurance pays out. [9.4.2, 13.3.2, 15.4.4, Box 22-1]
Broader context	• Index-based weather insurance is considered well suited to the agricultural sector in developing countries. • The mechanism allows risk to be shared across communities, with costs spread over time, while overcoming obstacles to traditional agricultural and disaster insurance markets. It can be integrated with other strategies such as microfinance and social protection programs. • Risk-based premiums can help encourage adaptive responses and foster risk awareness and risk reduction by providing financial incentives to policyholders to reduce their risk profile. • Challenges can be associated with limited availability of accurate weather data and difficulties in establishing which weather conditions cause losses. Basis risk (i.e., farmers suffer losses but no payout is triggered based on weather data) can promote distrust. There can also be difficulty in scaling up pilot schemes. • Insurance for work programs can enable cash-poor farmers to work for insurance premiums by engaging in community-identified disaster risk reduction projects. [10.7.4 to 10.7.6, 13.3.2, 15.4.4, Table 10-7, Boxes 22-1 and 25-7]

Continued next page →

for sea level rise has evolved considerably over the past 2 decades and shows a diversity of approaches, although its implementation remains piecemeal (*high confidence*). Adaptive capacity is generally high in many human systems, but implementation faces major constraints especially for transformational responses at local and community levels. [25.4, 25.10, Table 25-2, Boxes 25-1, 25-2, and 25-9]

- In North America, governments are engaging in incremental adaptation assessment and planning, particularly at the municipal level (*high confidence*). Some proactive adaptation is occurring to protect longer-term investments in energy and public infrastructure. [26.7 to 26.9]
- In Central and South America, ecosystem-based adaptation including protected areas, conservation agreements, and community management of natural areas is occurring (*high confidence*). Resilient crop varieties, climate forecasts, and integrated water resources management are being adopted within the agricultural sector in some areas. [27.3]
- In the Arctic, some communities have begun to deploy adaptive co-management strategies and communications infrastructure, combining traditional and scientific knowledge (*high confidence*). [28.2, 28.4]
- In small islands, which have diverse physical and human attributes, community-based adaptation has been shown to generate larger benefits when delivered in conjunction with other development activities (*high confidence*). [29.3, 29.6, Table 29-3, Figure 29-1]
- In both the open ocean and coastal areas, international cooperation and marine spatial planning are starting to facilitate adaptation to climate change, with constraints from challenges of spatial scale and governance issues (*high confidence*). Observed coastal adaptation includes major projects (e.g., Thames Estuary, Venice Lagoon, Delta Works) and specific practices in some countries (e.g., Netherlands, Australia, Bangladesh). [5.5, 7.3, 15.4, 30.6, Box CC-EA]

Table TS.2 presents examples of how climate extremes and change, as well as exposure and vulnerability at the scale of risk management, shape adaptation actions and approaches to reducing vulnerability and enhancing resilience.

A-3. The Decision-making Context

Climate variability and extremes have long been important in many decision-making contexts. Climate-related risks are now evolving over

Table TS.2 (continued)

Relocation of agricultural industries in Australia	
Exposure and vulnerability	Crops sensitive to changing patterns of temperature, rainfall, and water availability. [7.3, 7.5.2]
Climate information at the global scale	**Observed:** • *Very likely* decrease in the number of cold days and nights and increase in the number of warm days and nights, on the global scale between 1951 and 2010. [WGI AR5 2.6.1] • *Medium confidence* that the length and frequency of warm spells, including heat waves, has increased globally since 1950. [WGI AR5 2.6.1] • *Medium confidence* in precipitation change over global land areas since 1950. [WGI AR5 2.5.1] • Since 1950 the number of heavy precipitation events over land has *likely* increased in more regions than it has decreased. [WGI AR5 2.6.2] • *Low confidence* in a global-scale observed trend in drought or dryness (lack of rainfall). [WGI AR5 2.6.2] **Projected:** • *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global mean temperatures increase, for events defined as extremes on both daily and seasonal time scales. [WGI AR5 12.4.3] • *Virtually certain* increase in global precipitation as global mean surface temperature increases. [WGI AR5 12.4.1] • Regional to global-scale projected decreases in soil moisture and increased risk of agricultural drought are *likely* in presently dry regions, and are projected with *medium confidence* by the end of this century under the RCP8.5 scenario. [WGI AR5 12.4.5] • Globally, for short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 12.4.5]
Climate information at the regional scale	**Observed:** • Cool extremes rarer and hot extremes more frequent and intense over Australia and New Zealand, since 1950 (*high confidence*). [Table 25-1] • *Likely* increase in heat wave frequency since 1950 in large parts of Australia. [WGI AR5 2.6.1] • Late autumn/winter decreases in precipitation in southwestern Australia since the 1970s and southeastern Australia since the mid-1990s, and annual increases in precipitation in northwestern Australia since the 1950s (*very high confidence*). [Table 25-1] • Mixed or insignificant trends in annual daily precipitation extremes, but a tendency to significant increase in annual intensity of heavy precipitation in recent decades for sub-daily events in Australia (*high confidence*). [Table 25-1] **Projected:** • Hot days and nights more frequent and cold days and nights less frequent during the 21st century in Australia and New Zealand (*high confidence*). [Table 25-1] • Annual decline in precipitation over southwestern Australia (*high confidence*) and elsewhere in southern Australia (*medium confidence*). Reductions strongest in the winter half-year (*high confidence*). [Table 25-1] • Increase in most regions in the intensity of rare daily rainfall extremes and in sub-daily extremes (*medium confidence*) in Australia and New Zealand. [Table 25-1] • Drought occurrence to increase in southern Australia (*medium confidence*). [Table 25-1] • Snow depth and snow area to decline in Australia (*very high confidence*). [Table 25-1] • Freshwater resources projected to decline in far southeastern and far southwestern Australia (*high confidence*). [25.5.2]
Description	Industries and individual farmers are relocating parts of their operations, for example for rice, wine, or peanuts in Australia, or are changing land use *in situ* in response to recent climate change or expectations of future change. For example, there has been some switching from grazing to cropping in southern Australia. Adaptive movement of crops has also occurred elsewhere. [7.5.1, 25.7.2, Table 9-7, Box 25-5]
Broader context	• Considered transformational adaptation in response to impacts of climate change. • Positive or negative implications for the wider communities in origin and destination regions. [25.7.2, Box 25-5]

time due to both climate change and development. This section builds from existing experience with decision making and risk management. It creates a foundation for understanding the report's assessment of future climate-related risks and potential responses.

Responding to climate-related risks involves decision making in a changing world, with continuing uncertainty about the severity and timing of climate-change impacts and with limits to the effectiveness of adaptation (*high confidence*). Iterative risk management is a useful framework for decision making in complex situations characterized by large potential consequences, persistent uncertainties, long timeframes, potential for learning, and multiple climatic and non-climatic influences changing over time. See Figure TS.4. Assessment of the widest possible range of potential impacts, including low-probability outcomes with large consequences, is central to understanding the benefits and trade-offs of alternative risk management actions. The complexity of adaptation actions across scales and contexts means that monitoring and learning are important components of effective adaptation. [2.1 to 2.4, 3.6, 14.1 to 14.3, 15.2 to 15.4, 16.2 to 16.4, 17.1 to 17.3, 17.5, 20.6, 22.4, 25.4, Figure 1-5]

Adaptation and mitigation choices in the near term will affect the risks of climate change throughout the 21st century (*high confidence*). Figure TS.5 illustrates projected climate futures under a low-emission mitigation scenario and a high-emission scenario [Representative Concentration Pathways (RCPs) 2.6 and 8.5], along with observed temperature and precipitation changes. The benefits of adaptation and mitigation occur over different but overlapping timeframes. Projected global temperature increase over the next few decades is similar across emission scenarios (Figure TS.5A, middle panel) (WGI AR5 Section 11.3). During this near-term era of committed climate change, risks will evolve as socioeconomic trends interact with the changing climate. Societal responses, particularly adaptations, will influence near-term outcomes. In the second half of the 21st century and beyond, global temperature increase diverges across emission scenarios (Figure TS.5A, middle and bottom panels) (WGI AR5 Section 12.4 and Table SPM.2). For this longer-term era of climate options, near-term and longer-term adaptation and mitigation, as well as development pathways, will determine the risks of climate change. [2.5, 21.2, 21.3, 21.5, Box CC-RC]

Assessment of risks in the WGII AR5 relies on diverse forms of evidence. Expert judgment is used to integrate evidence into evaluations of risks. Forms of evidence include, for example, empirical observations, experimental results, process-based understanding, statistical approaches, and simulation and descriptive models. Future

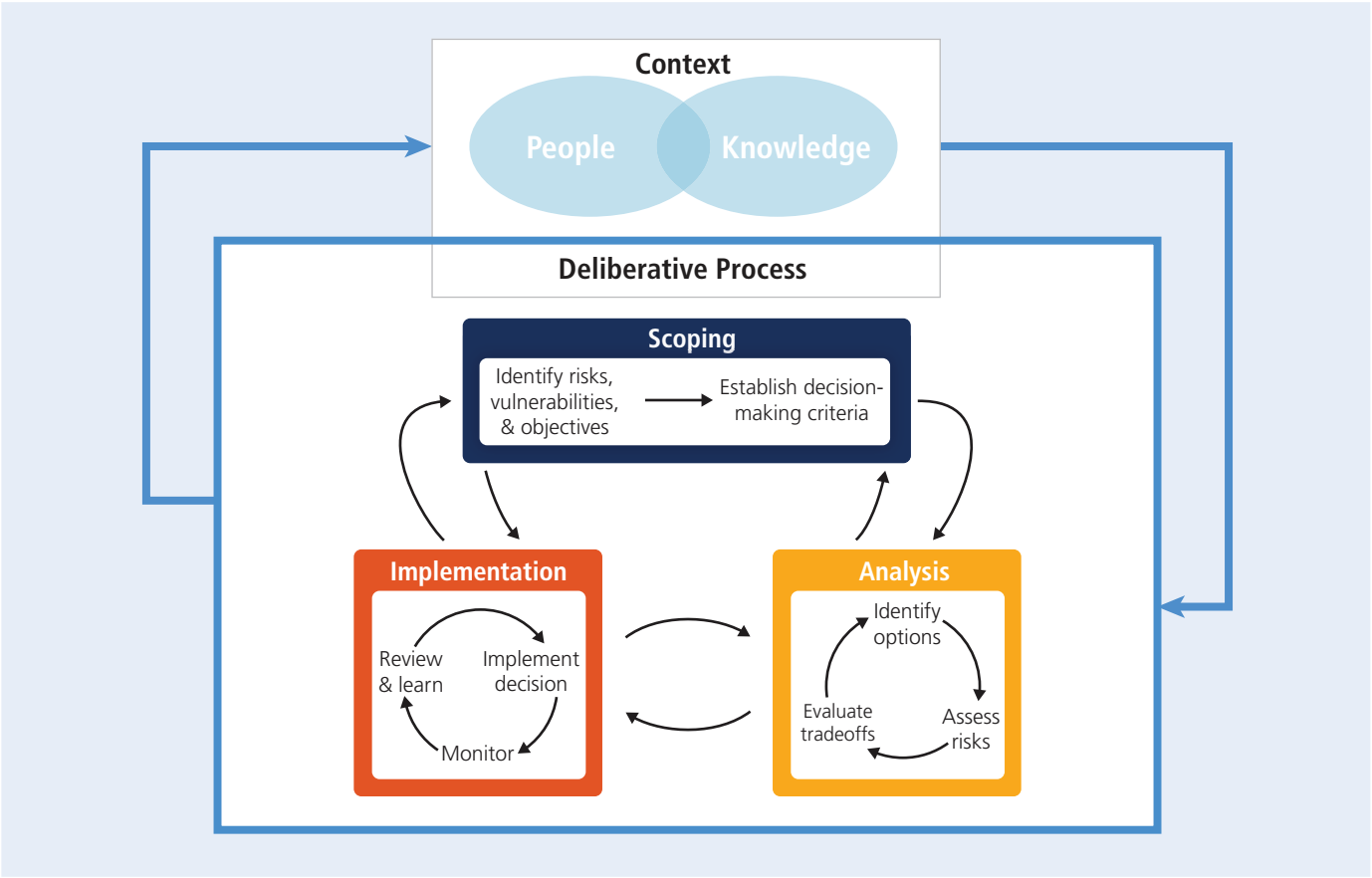


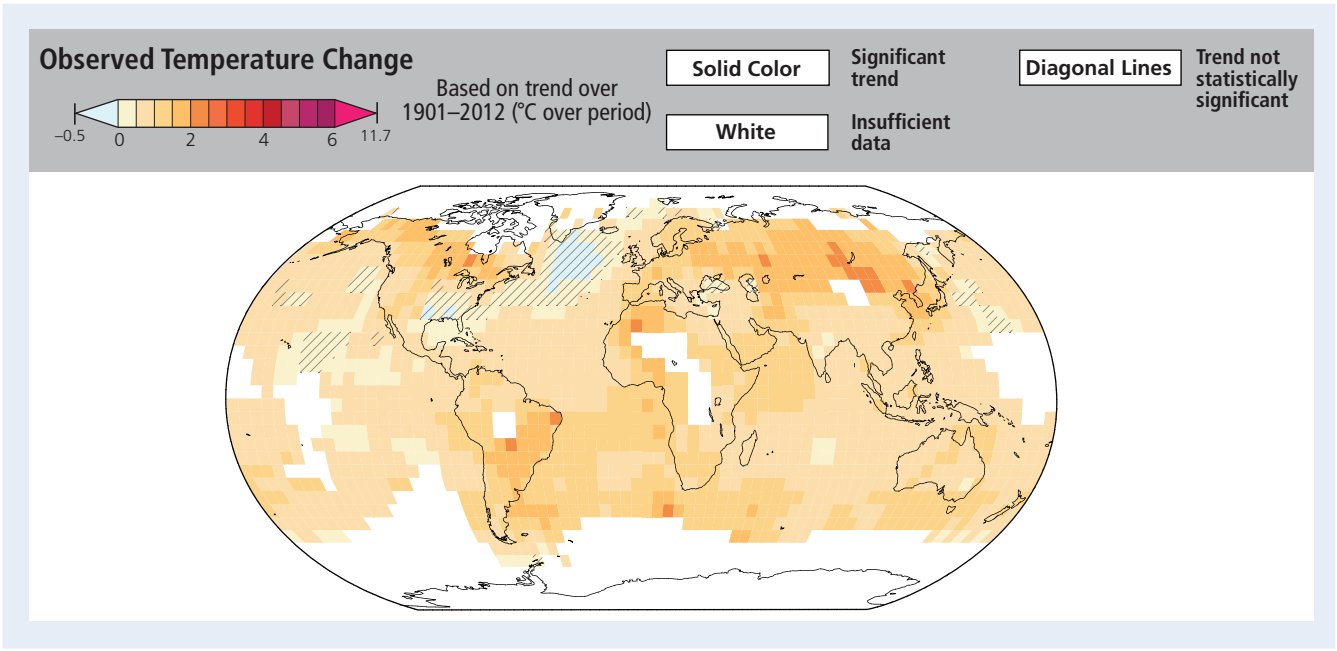
Figure TS.4 | Climate-change adaptation as an iterative risk management process with multiple feedbacks. People and knowledge shape the process and its outcomes. [Figure 2-1]

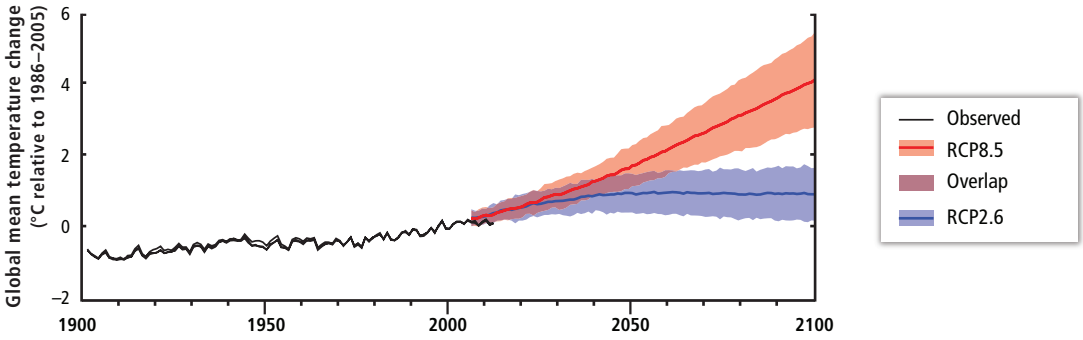
risks related to climate change vary substantially across plausible alternative development pathways, and the relative importance of development and climate change varies by sector, region, and time period (*high confidence*). Scenarios are useful tools for characterizing possible future socioeconomic pathways, climate change and its risks, and policy implications. Climate-model projections informing evaluations of risks in this report are generally based on the RCPs (Figure TS.5), as well as the older IPCC *Special Report on Emissions Scenarios* (SRES) scenarios. [1.1, 1.3, 2.2, 2.3, 19.6, 20.2, 21.3, 21.5, 26.2, Box CC-RC; WGI AR5 Box SPM.1]

Scenarios can be divided into those that explore how futures may unfold under various drivers (problem exploration) and those that test how various interventions may play out (solution exploration) (*robust evidence, high agreement*). Adaptation approaches address uncertainties associated with future climate and socioeconomic conditions and with the diversity of specific contexts (*medium evidence*, *high agreement*). Although many national studies identify a variety of strategies and approaches for adaptation, they can be classified into two broad categories: "top-down" and "bottom-up" approaches. The top-down approach is a scenario-impact approach, consisting of downscaled climate projections, impact assessments, and formulation of strategies and options. The bottom-up approach is a vulnerability-threshold approach, starting with the identification of vulnerabilities, sensitivities, and thresholds for specific sectors or communities. Iterative assessments of impacts and adaptation in the top-down approach and building adaptive capacity of local communities are typical strategies for responding to uncertainties. [2.2, 2.3, 15.3]

Uncertainties about future vulnerability, exposure, and responses of interlinked human and natural systems are large (*high confidence*). This motivates exploration of a wide range of socioeconomic futures in assessments of risks. Understanding future vulnerability, exposure, and response capacity of interlinked human and natural systems is challenging due to the number of interacting social, economic, and cultural factors, which have been incompletely considered to date. These factors include wealth and its distribution across society, demographics, migration, access to technology and information, employment patterns, the quality of adaptive responses, societal values, governance structures, and institutions to resolve conflicts. International dimensions such as trade and relations among states are also important for understanding the risks of climate change at regional scales. [11.3, 12.6, 21.3 to 21.5, 25.3, 25.4, 25.11, 26.2]

(A)





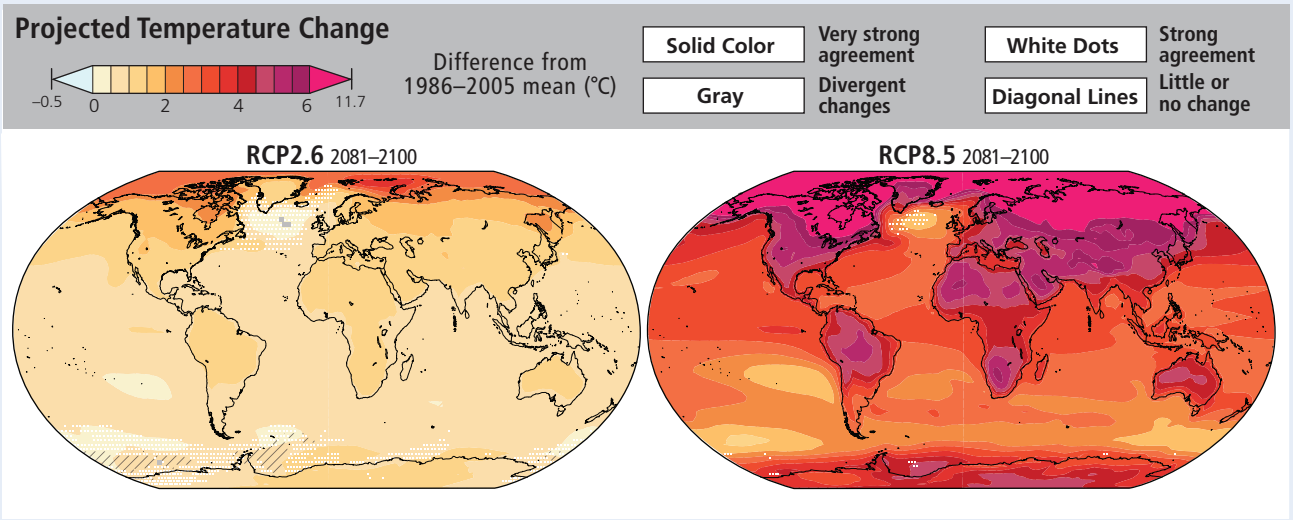


Figure TS.5

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Figure TS.5 (continued)

(B)

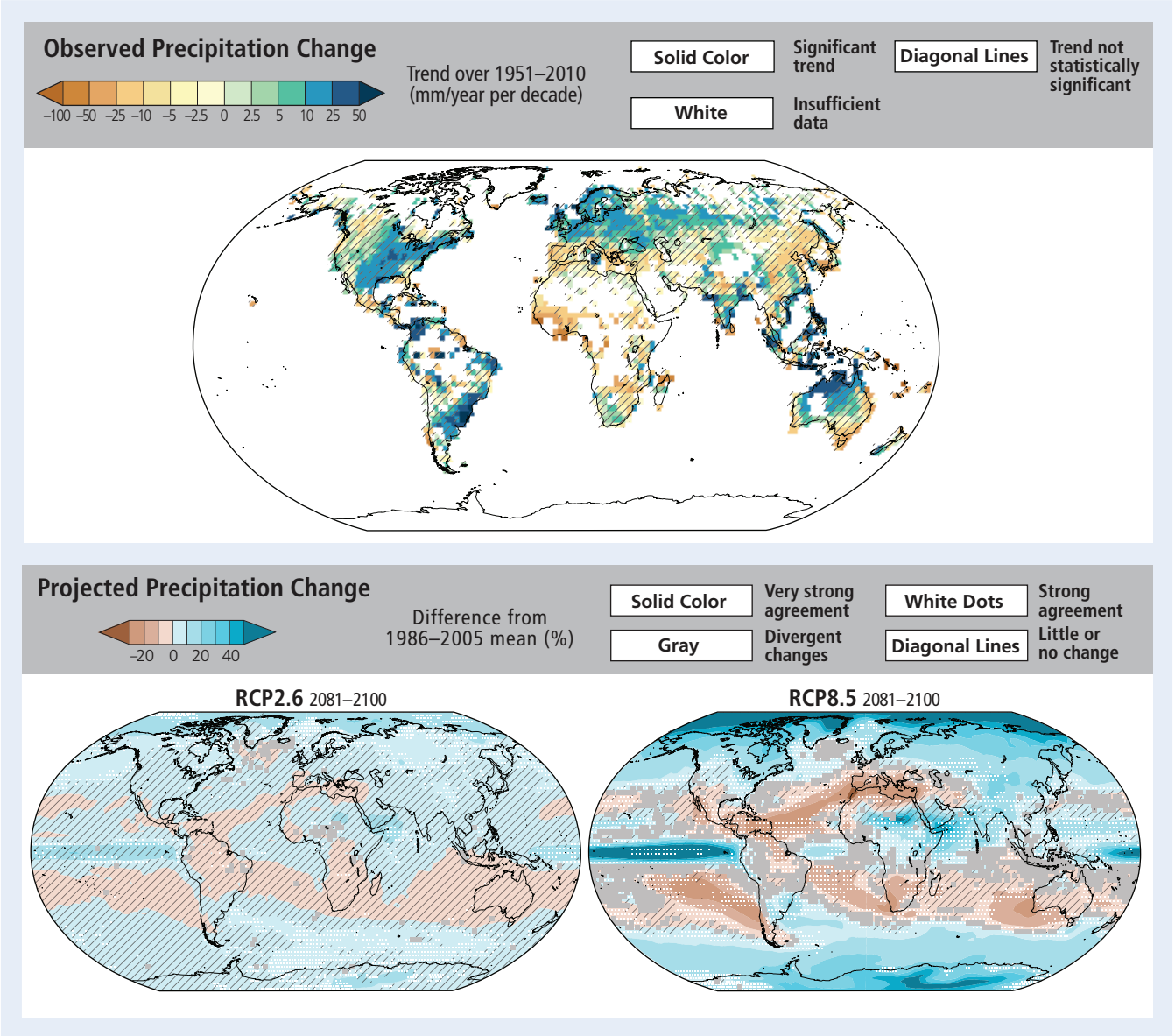


Figure TS.5 | Observed and projected changes in annual average surface temperature (A) and precipitation (B). This figure informs understanding of climate-related risks in the WGII AR5. It illustrates changes observed to date and projected changes under continued high emissions and under ambitious mitigation.

Technical details: (A, top panel) Map of observed annual mean temperature change from 1901–2012, derived from a linear trend. Observed data (range of grid-point values: –0.53 to 2.50°C over period) are from WGI AR5 Figures SPM.1 and 2.21. (B, top panel) Map of observed annual precipitation change from 1951–2010, derived from a linear trend. Observed data (range of grid-point values: –185 to 111 mm/year per decade) are from WGI AR5 Figures SPM.2 and 2.29. For observed temperature and precipitation, trends have been calculated where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where trends are significant at the 10% level. Diagonal lines indicate areas where trends are not significant. (A, middle panel) Observed and projected future global annual mean temperature relative to 1986–2005. Observed warming from 1850–1900 to 1986–2005 is 0.61°C (5–95% confidence interval: 0.55 to 0.67°C). Black lines show temperature estimates from three datasets. Blue and red lines and shading denote the ensemble mean and ±1.64 standard deviation range, based on Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations from 32 models for RCP2.6 and 39 models for RCP8.5. (A and B, bottom panel) CMIP5 multi-model mean projections of annual mean temperature changes (A) and mean percent changes in annual mean precipitation (B) for 2081–2100 under RCP2.6 and 8.5, relative to 1986–2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-yr means) and ≥90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where ≥66% of models show change greater than the baseline variability and ≥66% of models agree on sign of change. Gray indicates areas with divergent changes, where ≥66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where <66% of models show change greater than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. For temperature projections, analysis uses model data (range of grid-point values across RCP2.6 and 8.5: 0.06 to 11.71°C) from WGI AR5 Figure SPM.8. For precipitation projections, analysis uses model data (range of grid-point values: –9 to 22% for RCP2.6 and –34 to 112% for RCP8.5) from WGI AR5 Figure SPM.8, Box 12.1, and Annex I. For a full description of methods, see Box CC-RC. See also Annex I of WGI AR5. [Boxes 21-2 and CC-RC; WGI AR5 2.4 and 2.5, Figures SPM.1, SPM.2, SPM.7, SPM.8, 2.21, and 2.29]

B: FUTURE RISKS AND OPPORTUNITIES FOR ADAPTATION

This section presents future risks and more limited potential benefits across sectors and regions, examining how they are affected by the magnitude and rate of climate change and by socioeconomic choices. It also assesses opportunities for reducing impacts and managing risks through adaptation and mitigation. The section examines the distribution of risks across populations with contrasting vulnerability and adaptive capacity, across sectors where metrics for quantifying impacts may be quite different, and across regions with varying traditions and resources. The assessment features interactions across sectors and regions and among climate change and other stressors. For different sectors and regions, the section describes risks and potential benefits over the next few decades, the near-term era of committed climate change. Over this timeframe, projected global temperature increase is similar across emission scenarios. The section also provides information on risks and potential benefits in the second half of the 21st century and beyond, the longer-term era of climate options. Over this longer term, global temperature increase diverges across emission scenarios, and the assessment distinguishes potential outcomes for 2°C and 4°C global mean temperature increase above preindustrial levels. The section elucidates how and when choices matter in reducing future risks, highlighting the differing timeframes for mitigation and adaptation benefits.

B-1. Key Risks across Sectors and Regions

Key risks are potentially severe impacts relevant to Article 2 of the UN Framework Convention on Climate Change, which refers to "dangerous anthropogenic interference with the climate system." Risks are considered key due to high hazard or high vulnerability of societies and systems exposed, or both. Identification of key risks was based on expert judgment using the following specific criteria: large magnitude, high probability, or irreversibility of impacts; timing of impacts; persistent vulnerability or exposure contributing to risks; or limited potential to reduce risks through adaptation or mitigation. Key risks are integrated into five complementary and overarching reasons for concern (RFCs) in Box TS.5.

The key risks that follow, all of which are identified with *high confidence*, span sectors and regions. Each of these key risks contributes to one or more RFCs. Roman numerals correspond to entries in Table TS.3, which further illustrates relevant examples and interactions. [19.2 to 19.4, 19.6, Table 19-4, Boxes 19-2 and CC-KR]

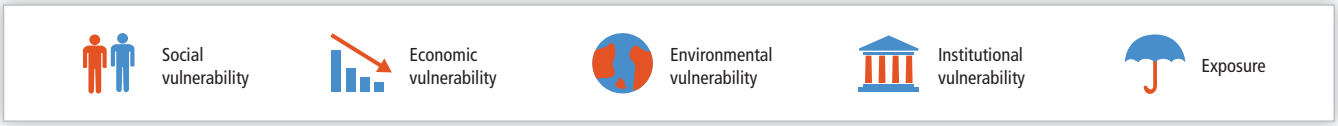
i) Risk of death, injury, ill-health, or disrupted livelihoods in low-lying coastal zones and small island developing states and other small islands, due to storm surges, coastal flooding, and sea level rise. See RFCs 1 to 5. [5.4, 8.2, 13.2, 19.2 to 19.4, 19.6, 19.7, 24.4, 24.5, 26.7, 26.8, 29.3, 30.3, Tables 19-4 and 26-1, Figure 26-2, Boxes 25-1, 25-7, and CC-KR]

Table TS.3 | A selection of the hazards, key vulnerabilities, key risks, and emergent risks identified in chapters of this report. The examples underscore the complexity of risks determined by various interacting climate-related hazards, non-climatic stressors, and multifaceted vulnerabilities (see also Figure TS.1). Vulnerabilities identified as key arise when exposure to hazards combines with social, institutional, economic, or environmental vulnerability, as indicated by icons in the table. Emergent risks arise from complex system interactions. Roman numerals correspond with key risks listed in Section B-1. [19.6, Table 19-4]

No.	Hazard	Key vulnerabilities		Key risks	Emergent risks
i	Sea level rise and coastal flooding including storm surges [5.4.3, 8.1.4, 8.2.3, 8.2.4, 13.1.4, 13.2.2, 24.4, 24.5, 26.7, 26.8, 29.3, 30.3.1, Boxes 25-1 and 25-7; WGI AR5 3.7, 13.5, Table 13-5]	High exposure of people, economic activity, and infrastructure in low-lying coastal zones and Small Island Developing States (SIDS) and other small islands Urban population unprotected due to substandard housing and inadequate insurance. Marginalized rural population with multidimensional poverty and limited alternative livelihoods Insufficient local governmental attention to disaster risk reduction		Death, injury, and disruption to livelihoods, food supplies, and drinking water Loss of common-pool resources, sense of place, and identity, especially among indigenous populations in rural coastal zones	Interaction of rapid urbanization, sea level rise, increasing economic activity, disappearance of natural resources, and limits of insurance; burden of risk management shifted from the state to those at risk leading to greater inequality
ii	Extreme precipitation and inland flooding [3.2.7, 3.4.8, 8.2.3, 8.2.4, 13.2.1, 25.10, 26.3, 26.7, 26.8, 27.3.5, Box 25-8; WGI AR5 11.3.2]	Large numbers of people exposed in urban areas to flood events, particularly in low-income informal settlements Overwhelmed, aging, poorly maintained, and inadequate urban drainage infrastructure and limited ability to cope and adapt due to marginalization, high poverty, and culturally imposed gender roles Inadequate governmental attention to disaster risk reduction		Death, injury, and disruption of human security, especially among children, elderly, and disabled persons	Interaction of increasing frequency of intense precipitation, urbanization, and limits of insurance; burden of risk management shifted from the state to those at risk leading to greater inequality, eroded assets due to infrastructure damage, abandonment of urban districts, and the creation of high risk/high poverty spatial traps
iii	Novel hazards yielding systemic risks [8.1.4, 8.2.4, 10.2, 10.3, 12.6, 23.9, 25.10, 26.7, 26.8; WGI AR5 11.3.2]	Populations and infrastructure exposed and lacking historical experience with these hazards Overly hazard-specific management planning and infrastructure design, and/or low forecasting capability		Failure of systems coupled to electric power system, e.g., drainage systems reliant on electric pumps or emergency services reliant on telecommunications. Collapse of health and emergency services in extreme events	Interactions due to dependence on coupled systems lead to magnification of impacts of extreme events. Reduced social cohesion due to loss of faith in management institutions undermines preparation and capacity for response.
iv	Increasing frequency and intensity of extreme heat, including urban heat island effect [8.2.3, 11.3, 11.4.1, 13.2, 23.5.1, 24.4.6, 25.8.1, 26.6, 26.8, Box CC-HS; WGI AR5 11.3.2]	Increasing urban population of the elderly, the very young, expectant mothers, and people with chronic health problems in settlements subject to higher temperatures Inability of local organizations that provide health, emergency, and social services to adapt to new risk levels for vulnerable groups		Increased mortality and morbidity during periods of extreme heat	Interaction of demographic shifts with changes in regional temperature extremes, local heat island, and air pollution Overloading of health and emergency services. Higher mortality, morbidity, and productivity loss among manual workers in hot climates

Table TS.3 (continued)

No.	Hazard	Key vulnerabilities		Key risks	Emergent risks
v	Warming, drought, and precipitation variability [7.3 to 7.5, 11.3, 11.6.1, 13.2, 19.3.2, 19.4.1, 22.3.4, 24.4, 26.8, 27.3.4; WGI AR5 11.3.2]	Poorer populations in urban and rural settings are susceptible to resulting food insecurity; includes particularly farmers who are net food buyers and people in low-income, agriculturally dependent economies that are net food importers. Limited ability to cope among the elderly and female-headed households		Risk of harm and loss of life due to reversal of progress in reducing malnutrition	Interactions of climate changes, population growth, reduced productivity, biofuel crop cultivation, and food prices with persistent inequality, and ongoing food insecurity for the poor increase malnutrition, giving rise to larger burden of disease. Exhaustion of social networks reduces coping capacity.
vi	Drought [3.2.7, 3.4.8, 3.5.1, 8.2.3, 8.2.4, 9.3.3, 9.3.5, 13.2.1, 19.3.2, 24.4, 25.7, Box 25-5; WGI AR5 12.4.1, 12.4.5]	Urban populations with inadequate water services. Existing water shortages (and irregular supplies), and constraints on increasing supplies Lack of capacity and resilience in water management regimes including rural–urban linkages		Insufficient water supply for people and industry yielding severe harm and economic impacts	Interaction of urbanization, infrastructure insufficiency, groundwater depletion
		Poorly endowed farmers in drylands or pastoralists with insufficient access to drinking and irrigation water Limited ability to compensate for losses in water-dependent farming and pastoral systems, and conflict over natural resources Lack of capacity and resilience in water management regimes, inappropriate land policy, and misperception and undermining of pastoral livelihoods		Loss of agricultural productivity and/or income of rural people. Destruction of livelihoods particularly for those depending on water-intensive agriculture. Risk of food insecurity	Interactions across human vulnerabilities: deteriorating livelihoods, poverty traps, heightened food insecurity, decreased land productivity, rural outmigration, and increase in new urban poor in developing countries. Potential tipping point in rain-fed farming system and/or pastoralism
vii	Rising ocean temperature, ocean acidification, and loss of Arctic sea ice [5.4.2, 6.3.1, 6.3.2, 7.4.2, 9.3.5, 22.3.2, 24.4, 25.6, 27.3.3, 28.2, 28.3, 29.3.1, 30.5, 30.6, Boxes CC-OA and CC-CR; WGI AR5 11.3.3]	High susceptibility of warm-water coral reefs and respective ecosystem services for coastal communities; high susceptibility of polar systems, e.g., to invasive species Susceptibility of coastal and SIDS fishing communities depending on these ecosystem services; and of Arctic settlements and culture		Loss of coral cover, Arctic species, and associated ecosystems with reduction of biodiversity and potential losses of important ecosystem services. Risk of loss of endemic species, mixing of ecosystem types, and increased dominance of invasive organisms	Interactions of stressors such as acidification and warming on calcareous organisms enhancing risk
viii	Rising land temperatures, and changes in precipitation patterns and in frequency and intensity of extreme heat [4.3.4, 19.3.2, 22.4.5, 27.3, Boxes 23-1 and CC-WE; WGI AR5 11.3.2]	Susceptibility of human systems, agro-ecosystems, and natural ecosystems to (1) loss of regulation of pests and diseases, fire, landslide, erosion, flooding, avalanche, water quality, and local climate; (2) loss of provision of food, livestock, fiber, and bioenergy; (3) loss of recreation, tourism, aesthetic and heritage values, and biodiversity		Reduction of biodiversity and potential losses of important ecosystem services. Risk of loss of endemic species, mixing of ecosystem types, and increased dominance of invasive organisms	Interaction of social-ecological systems with loss of ecosystem services on which they depend



ii) Risk of severe ill-health and disrupted livelihoods for large urban populations due to inland flooding in some regions. See RFCs 2 and 3. [3.4, 3.5, 8.2, 13.2, 19.6, 25.10, 26.3, 26.8, 27.3, Tables 19-4 and 26-1, Boxes 25-8 and CC-KR]

iii) Systemic risks due to extreme weather events leading to breakdown of infrastructure networks and critical services such as electricity, water supply, and health and emergency services. See RFCs 2 to 4. [5.4, 8.1, 8.2, 9.3, 10.2, 10.3, 12.6, 19.6, 23.9, 25.10, 26.7, 26.8, 28.3, Table 19-4, Boxes CC-KR and CC-HS]

iv) Risk of mortality and morbidity during periods of extreme heat, particularly for vulnerable urban populations and those working outdoors in urban or rural areas. See RFCs 2 and 3. [8.1, 8.2, 11.3, 11.4, 11.6, 13.2, 19.3, 19.6, 23.5, 24.4, 25.8, 26.6, 26.8, Tables 19-4 and 26-1, Boxes CC-KR and CC-HS]

v) Risk of food insecurity and the breakdown of food systems linked to warming, drought, flooding, and precipitation variability and extremes, particularly for poorer populations in urban and rural settings. See RFCs 2 to 4. [3.5, 7.4, 7.5, 8.2, 8.3, 9.3, 11.3, 11.6, 13.2, 19.3, 19.4, 19.6, 22.3, 24.4, 25.5, 25.7, 26.5, 26.8, 27.3, 28.2, 28.4, Table 19-4, Box CC-KR]

vi) Risk of loss of rural livelihoods and income due to insufficient access to drinking and irrigation water and reduced agricultural productivity, particularly for farmers and pastoralists with minimal capital in semi-arid regions. See RFCs 2 and 3. [3.4, 3.5, 9.3, 12.2, 13.2, 19.3, 19.6, 24.4, 25.7, 26.8, Table 19-4, Boxes 25-5 and CC-KR]

vii) Risk of loss of marine and coastal ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for coastal livelihoods, especially for fishing communities in the tropics and the

Box TS.5 | Human Interference with the Climate System

Human influence on the climate system is clear (WGI AR5 SPM Section D.3; WGI AR5 Sections 2.2, 6.3, 10.3 to 10.6, 10.9). Yet determining whether such influence constitutes "dangerous anthropogenic interference" in the words of Article 2 of the UNFCCC involves both risk assessment and value judgments. Scientific assessment can characterize risks based on the likelihood, magnitude, and scope of potential consequences of climate change. Science can also evaluate risks varying spatially and temporally across alternative development pathways, which affect vulnerability, exposure, and level of climate change. Interpreting the potential danger of risks, however, also requires value judgments by people with differing goals and worldviews. Judgments about the risks of climate change depend on the relative importance ascribed to economic versus ecosystem assets, to the present versus the future, and to the distribution versus aggregation of impacts. From some perspectives, isolated or infrequent impacts from climate change may not rise to the level of dangerous anthropogenic interference, but accumulation of the same kinds of impacts could, as they become more widespread, more frequent, or more severe. The rate of climate change can also influence risks. This report assesses risks across contexts and through time, providing a basis for judgments about the level of climate change at which risks become dangerous.

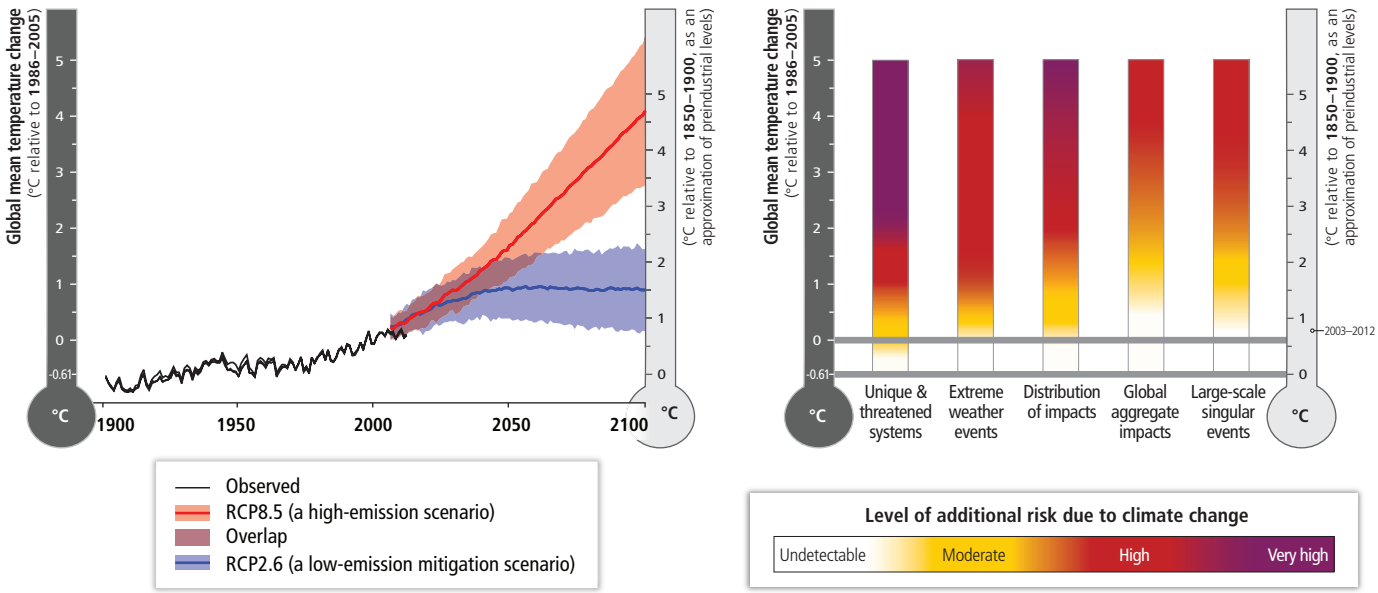
Five integrative reasons for concern (RFCs) provide a framework for summarizing key risks across sectors and regions. First identified in the IPCC Third Assessment Report, the RFCs illustrate the implications of warming and of adaptation limits for people, economies, and ecosystems. They provide one starting point for evaluating dangerous anthropogenic interference with the climate system. Risks for each RFC, updated based on assessment of the literature and expert judgments, are presented below and in Box TS.5 Figure 1. All temperatures below are given as global average temperature change relative to 1986–2005 ("recent").[1] [18.6, 19.6]

1) **Unique and threatened systems**: Some unique and threatened systems, including ecosystems and cultures, are already at risk from climate change (*high confidence*). The number of such systems at risk of severe consequences is higher with additional warming of around 1°C. Many species and systems with limited adaptive capacity are subject to very high risks with additional warming of 2°C, particularly Arctic-sea-ice and coral-reef systems.
2) **Extreme weather events**: Climate-change-related risks from extreme events, such as heat waves, extreme precipitation, and coastal flooding, are already moderate (*high confidence*) and high with 1°C additional warming (*medium confidence*). Risks associated with some types of extreme events (e.g., extreme heat) increase further at higher temperatures (*high confidence*).
3) **Distribution of impacts**: Risks are unevenly distributed and are generally greater for disadvantaged people and communities in countries at all levels of development. Risks are already moderate because of regionally differentiated climate-change impacts on crop production in particular (*medium* to *high confidence*). Based on projected decreases in regional crop yields and water availability, risks of unevenly distributed impacts are high for additional warming above 2°C (*medium confidence*).
4) **Global aggregate impacts**: Risks of global aggregate impacts are moderate for additional warming between 1–2°C, reflecting impacts to both Earth's biodiversity and the overall global economy (*medium confidence*). Extensive biodiversity loss with associated loss of ecosystem goods and services results in high risks around 3°C additional warming (*high confidence*). Aggregate economic damages accelerate with increasing temperature (*limited evidence*, *high agreement*), but few quantitative estimates have been completed for additional warming around 3°C or above.
5) **Large-scale singular events**: With increasing warming, some physical systems or ecosystems may be at risk of abrupt and irreversible changes. Risks associated with such tipping points become moderate between 0–1°C additional warming, due to early warning signs that both warm-water coral reef and Arctic ecosystems are already experiencing irreversible regime shifts (*medium confidence*). Risks increase disproportionately as temperature increases between 1–2°C additional warming and become high above 3°C, due to the potential for a large and irreversible sea level rise from ice sheet loss. For sustained warming greater than some threshold,[2] near-complete loss of the Greenland ice sheet would occur over a millennium or more, contributing up to 7 m of global mean sea level rise.

Continued next page →

[1] Observed warming from 1850–1900 to 1986–2005 is 0.61°C (5–95% confidence interval: 0.55 to 0.67°C). [WGI AR5 2.4]

[2] Current estimates indicate that this threshold is greater than about 1°C (*low confidence*) but less than about 4°C (*medium confidence*) sustained global mean warming above preindustrial levels. [WGI AR5 SPM, 5.8, 13.4, 13.5]



Box TS.5 Figure 1 | A global perspective on climate-related risks. Risks associated with reasons for concern are shown at right for increasing levels of climate change. The color shading indicates the additional risk due to climate change when a temperature level is reached and then sustained or exceeded. Undetectable risk (white) indicates no associated impacts are detectable and attributable to climate change. Moderate risk (yellow) indicates that associated impacts are both detectable and attributable to climate change with at least *medium confidence*, also accounting for the other specific criteria for key risks. High risk (red) indicates severe and widespread impacts, also accounting for the other specific criteria for key risks. Purple, introduced in this assessment, shows that very high risk is indicated by all specific criteria for key risks. [Figure 19-4] For reference, past and projected global annual average surface temperature is shown at left, as in Figure TS.5. [Figure RC-1, Box CC-RC; WGI AR5 Figures SPM.1 and SPM.7] Based on the longest global surface temperature dataset available, the observed change between the average of the period 1850–1900 and of the AR5 reference period (1986–2005) is 0.61°C (5–95% confidence interval: 0.55 to 0.67°C) [WGI AR5 SPM, 2.4], which is used here as an approximation of the change in global mean surface temperature since preindustrial times, referred to as the period before 1750. [WGI and WGII AR5 glossaries]

Arctic. See RFCs 1, 2, and 4. [5.4, 6.3, 7.4, 9.3, 19.5, 19.6, 22.3, 25.6, 27.3, 28.2, 28.3, 29.3, 30.5 to 30.7, Table 19-4, Boxes CC-OA, CC-CR, CC-KR, and CC-HS]

viii) Risk of loss of terrestrial and inland water ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for livelihoods. See RFCs 1, 3, and 4. [4.3, 9.3, 19.3 to 19.6, 22.3, 25.6, 27.3, 28.2, 28.3, Table 19-4, Boxes CC-KR and CC-WE]

Many key risks constitute particular challenges for the least developed countries and vulnerable communities, given their limited ability to cope.

Increasing magnitudes of warming increase the likelihood of severe, pervasive, and irreversible impacts. Some risks of climate change are considerable at 1°C or 2°C above preindustrial levels (as shown in Box TS.5). Global climate change risks are high to very high with global mean temperature increase of 4°C or more above preindustrial levels in all reasons for concern (Box TS.5), and include severe and widespread impacts on unique and threatened systems, substantial species extinction, large risks to global and regional food security, and the combination of high temperature and humidity compromising normal human activities, including growing food or working outdoors in some areas for parts of the year (*high confidence*). See Box TS.6. The precise levels of climate change sufficient to trigger tipping points (thresholds for abrupt and irreversible change) remain uncertain, but the risk associated with crossing multiple tipping points in the earth system or in interlinked human and natural systems increases with rising temperature (*medium confidence*). [4.2, 4.3, 11.8, 19.5, 19.7, 26.5, Box CC-HS]

The overall risks of climate change impacts can be reduced by limiting the rate and magnitude of climate change. Risks are reduced substantially under the assessed scenario with the lowest temperature projections (RCP2.6 – low emissions) compared to the highest temperature projections (RCP8.5 – high emissions), particularly in the second half of the 21st century (*very high confidence*). Examples include reduced risk of negative agricultural yield impacts; of water scarcity; of major challenges to urban settlements and infrastructure from sea level rise; and of adverse impacts from heat extremes, floods, and droughts in areas where increased occurrence of these extremes is projected. Reducing climate change can also reduce the scale of adaptation that might be required. Under all assessed scenarios for adaptation and mitigation, some risk from adverse impacts remains (*very high confidence*). Because mitigation reduces the rate as well as the magnitude of warming, it also increases the time available for adaptation to a particular level of climate change, potentially by several decades, but adaptation cannot generally overcome all climate change effects. In addition to biophysical limits to adaptation for example under high temperatures, some adaptation options will be too costly or resource intensive or will be cost ineffective until climate change effects grow to merit investment costs (*high confidence*). Some mitigation or adaptation options also pose risks. [3.4, 3.5, 4.2, 4.4, 16.3, 16.6, 17.2, 19.7, 20.3, 22.4, 22.5, 25.10, Tables 3-2, 8-3, and 8-6, Boxes 16-3 and 25-1]

B-2. Sectoral Risks and Potential for Adaptation

For the near-term era of committed climate change (the next few decades) and the longer-term era of climate options (the second half

Box TS.6 | Consequences of Large Temperature Increase

This box provides a selection of salient climate change impacts projected for large temperature rise. Warming levels described here (e.g., 4°C warming) refer to global mean temperature increase above preindustrial levels, unless otherwise indicated.

With 4°C warming, climate change is projected to become an increasingly important driver of impacts on ecosystems, becoming comparable with land-use change. [4.2, 19.5] A number of studies project large increases in water stress, groundwater supplies, and drought in a number of regions with greater than 4°C warming, and decreases in others, generally placing already arid regions at greater water stress. [19.5]

Risks of large-scale singular events such as ice sheet disintegration, methane release from clathrates, and onset of long-term droughts in areas such as southwest North America [19.6, Box 26-1; WGI AR5 12.4, 12.5, 13.4], as well as regime shifts in ecosystems and substantial species loss [4.3, 19.6], are higher with increased warming. Sustained warming greater than some threshold would lead to the near-complete loss of the Greenland ice sheet over a millennium or more, causing a global mean sea level rise of up to 7 m (*high confidence*); current estimates indicate that the threshold is greater than about 1°C (*low confidence*) but less than about 4°C (*medium confidence*) global mean warming. [WGI AR5 SPM, 5.8, 13.4, 13.5] Abrupt and irreversible ice loss from a potential instability of marine-based areas of the Antarctic ice sheet in response to climate forcing is possible, but current evidence and understanding is insufficient to make a quantitative assessment. [19.6; WGI AR5 SPM, 5.8, 13.4, 13.5] Sea level rise of 0.45 to 0.82 m (mean 0.63 m) is *likely* by 2081–2100 under RCP8.5 (*medium confidence*) [WGI AR5 Tables SPM.2 and 13.5], with sea level continuing to rise beyond 2100.

The Atlantic Meridional Overturning Circulation (AMOC) will *very likely* weaken over the 21st century, with a best estimate of 34% loss (range 12 to 54%) under RCP8.5. [WGI AR5 SPM, 12.4] The release of carbon dioxide (CO_2) or methane (CH_4) to the atmosphere from thawing permafrost carbon stocks over the 21st century is assessed to be in the range of 50 to 250 GtC for Representative Concentration Pathway 8.5 (RCP8.5) (*low confidence*). [WGI AR5 SPM, 6.4] A nearly ice-free Arctic Ocean in September before mid-century is *likely* under RCP8.5 (*medium confidence*). [WGI AR5 SPM, 11.3, 12.4, 12.5]

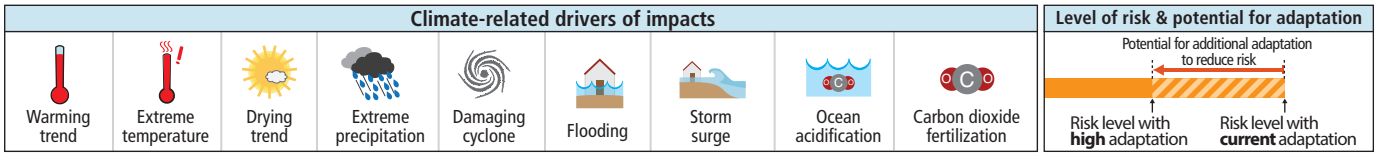
By 2100 for the high-emission scenario RCP8.5, the combination of high temperature and humidity in some areas for parts of the year is projected to compromise normal human activities, including growing food or working outdoors (*high confidence*). [11.8] Global temperature increases of ~4°C or more above late-20th-century levels, combined with increasing food demand, would pose large risks to food security globally and regionally (*high confidence*). [7.4, 7.5, Table 7-3, Figures 7-1, 7-4, and 7-7, Box 7-1]

Under 4°C warming, some models project large increases in fire risk in parts of the world. [4.3, Figure 4-6] 4°C warming implies a substantial increase in extinction risk for terrestrial and freshwater species, although there is *low agreement* concerning the fraction of species at risk. [4.3] Widespread coral reef mortality is expected with significant impacts on coral reef ecosystems (*high confidence*). [5.4, Box CC-CR] Assessments of potential ecological impacts at and above 4°C warming imply a high risk of extensive loss of biodiversity with concomitant loss of ecosystem services (*high confidence*). [4.3, 19.3, 19.5, Box 25-6]

Projected large increases in exposure to water stress, fluvial and coastal flooding, negative impacts on crop yields, and disruption of ecosystem function and services would represent large, potentially compounding impacts of climate change on society generally and on the global economy. [19.4 to 19.6]

of the 21st century and beyond), climate change will amplify existing climate-related risks and create new risks for natural and human systems, dependent on the magnitude and rate of climate change and on the vulnerability and exposure of interlinked human and natural systems. Some of these risks will be limited to a particular sector or region, and others will have cascading effects. To a lesser extent, climate change will also have some potential benefits. A selection of key sectoral risks identified with *medium* to *high confidence* is presented in Table TS.4.

Table TS.4 | Key sectoral risks from climate change and the potential for reducing risks through adaptation and mitigation. Key risks have been identified based on assessment of the relevant scientific, technical, and socioeconomic literature detailed in supporting chapter sections. Identification of key risks was based on expert judgment using the following specific criteria: large magnitude, high probability, or irreversibility of impacts; timing of impacts; persistent vulnerability or exposure contributing to risks; or limited potential to reduce risks through adaptation or mitigation. Each key risk is characterized as very low to very high for three timeframes: the present, near term (here, assessed over 2030–2040), and longer term (here, assessed over 2080–2100). The risk levels integrate probability and consequence over the widest possible range of potential outcomes, based on available literature. These potential outcomes result from the interaction of climate-related hazards, vulnerability, and exposure. Each risk level reflects total risk from climatic and non-climatic factors. For the near-term era of committed climate change, projected levels of global mean temperature increase do not diverge substantially for different emission scenarios. For the longer-term era of climate options, risk levels are presented for two scenarios of global mean temperature increase (2°C and 4°C above preindustrial levels). These scenarios illustrate the potential for mitigation and adaptation to reduce the risks related to climate change. For the present, risk levels were estimated for current adaptation and a hypothetical highly adapted state, identifying where current adaptation deficits exist. For the two future timeframes, risk levels were estimated for a continuation of current adaptation and for a highly adapted state, representing the potential for and limits to adaptation. Climate-related drivers of impacts are indicated by icons. Risk levels are not necessarily comparable because the assessment considers potential impacts and adaptation in different physical, biological, and human systems across diverse contexts. This assessment of risks acknowledges the importance of differences in values and objectives in interpretation of the assessed risk levels.

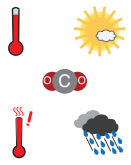
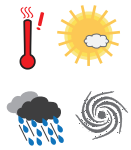
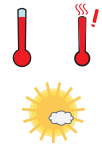


Global Risks

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Reduction in terrestrial carbon sink: Carbon stored in terrestrial ecosystems is vulnerable to loss back into the atmosphere, resulting from increased fire frequency due to climate change and the sensitivity of ecosystem respiration to rising temperatures (*medium confidence*) [4.2, 4.3]	• Adaptation options include managing land use (including deforestation), fire and other disturbances, and non-climatic stressors.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Boreal tipping point: Arctic ecosystems are vulnerable to abrupt change related to the thawing of permafrost, spread of shrubs in tundra, and increase in pests and fires in boreal forests (*medium confidence*) [4.3, Box 4-4]	• There are few adaptation options in the Arctic.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Amazon tipping point: Moist Amazon forests could change abruptly to less-carbon-dense, drought- and fire-adapted ecosystems (*low confidence*) [4.3, Box 4-3]	• Policy and market measures can reduce deforestation and fire.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Increased risk of species extinction: A large fraction of the species assessed is vulnerable to extinction due to climate change, often in interaction with other threats. Species with an intrinsically low dispersal rate, especially when occupying flat landscapes where the projected climate velocity is high, and species in isolated habitats such as mountaintops, islands, or small protected areas are especially at risk. Cascading effects through organism interactions, especially those vulnerable to phenological changes, amplify risk (*high confidence*) [4.3, 4.4]	• Adaptation options include reduction of habitat modification and fragmentation, pollution, over-exploitation, and invasive species; protected area expansion; assisted dispersal; and *ex situ* conservation.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Reduced growth and survival of commercially valuable shellfish and other calcifiers (e.g., reef-building corals, calcareous red algae) due to ocean acidification (*high confidence*) [5.3, 6.1, 6.3, 6.4, 30.3, Box CC-OA]	• Evidence for differential resistance and evolutionary adaptation of some species exists, but they are *likely* to be limited at higher CO_2 concentrations and temperatures. • Adaptation options include exploiting more resilient species or protecting habitats with low natural CO_2 levels, as well as reducing other stresses, mainly pollution, and limiting pressures from tourism and fishing.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Marine biodiversity loss with high rate of climate change (*medium confidence*) [6.3, 6.4, Table 30-4, Box CC-MB]	• Adaptation options are limited to reducing other stresses, mainly pollution, and limiting pressures from coastal human activities such as tourism and fishing.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high

Continued next page →

Table TS.4 (continued)

Global Risks				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Negative impacts on average crop yields and increases in yield variability due to climate change (*high confidence*) [7.2 to 7.5, Figure 7-5, Box 7-1]	• Projected impacts vary across crops and regions and adaptation scenarios, with about 10% of projections for the period 2030–2049 showing yield gains of more than 10%, and about 10% of projections showing yield losses of more than 25%, compared to the late 20th century. After 2050 the risk of more severe yield impacts increases and depends on the level of warming.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high
Urban risks associated with water supply systems (*high confidence*) [8.2, 8.3]	• Adaptation options include changes to network infrastructure as well as demand-side management to ensure sufficient water supplies and quality, increased capacities to manage reduced freshwater availability, and flood risk reduction.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high
Urban risks associated with energy systems (*high confidence*) [8.2, 8.4]	• Most urban centers are energy intensive, with energy-related climate policies focused only on mitigation measures. A few cities have adaptation initiatives underway for critical energy systems. There is potential for non-adapted, centralized energy systems to magnify impacts, leading to national and transboundary consequences from localized extreme events.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high
Urban risks associated with housing (*high confidence*) [8.3]	• Poor quality, inappropriately located housing is often most vulnerable to extreme events. Adaptation options include enforcement of building regulations and upgrading. Some city studies show the potential to adapt housing and promote mitigation, adaptation, and development goals simultaneously. Rapidly growing cities, or those rebuilding after a disaster, especially have opportunities to increase resilience, but this is rarely realized. Without adaptation, risks of economic losses from extreme events are substantial in cities with high-value infrastructure and housing assets, with broader economic effects possible.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high
Displacement associated with extreme events (*high confidence*) [12.4]	• Adaptation to extreme events is well understood, but poorly implemented even under present climate conditions. Displacement and involuntary migration are often temporary. With increasing climate risks, displacement is more likely to involve permanent migration.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high
Violent conflict arising from deterioration in resource-dependent livelihoods such as agriculture and pastoralism (*high confidence*) [12.5]	Adaptation options: • Buffering rural incomes against climate shocks, for example through livelihood diversification, income transfers, and social safety net provision • Early warning mechanisms to promote effective risk reduction • Well-established strategies for managing violent conflict that are effective but require significant resources, investment, and political will		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high
Declining work productivity, increasing morbidity (e.g., dehydration, heat stroke, and heat exhaustion), and mortality from exposure to heat waves. Particularly at risk are agricultural and construction workers as well as children, homeless people, the elderly, and women who have to walk long hours to collect water (*high confidence*) [13.2, Box 13-1]	• Adaptation options are limited for people who are dependent on agriculture and cannot afford agricultural machinery. • Adaptation options are limited in the construction sector where many poor people work under insecure arrangements. • Adaptation limits may be exceeded in certain areas in a +4°C world.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high
Reduced access to water for rural and urban poor people due to water scarcity and increasing competition for water (*high confidence*) [13.2, Box 13-1]	• Adaptation through reducing water use is not an option for the many people already lacking adequate access to safe water. Access to water is subject to various forms of discrimination, for instance due to gender and location. Poor and marginalized water users are unable to compete with water extraction by industries, large-scale agriculture, and other powerful users.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high

For extended summary of sectoral risks and the more limited potential benefits, see introductory overviews for each sector below and also Chapters 3 to 13.

Freshwater Resources

Freshwater-related risks of climate change increase significantly with increasing greenhouse gas concentrations (*robust evidence, high agreement*). The fraction of global population experiencing water scarcity and the fraction affected by major river floods increase with the level of warming in the 21st century. See, for example, Figure TS.6. [3.4, 3.5, 26.3, Table 3-2, Box 25-8]

Climate change over the 21st century is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions (*robust evidence, high agreement*), intensifying competition for water among sectors (*limited evidence, medium agreement*). In presently dry regions, drought frequency will *likely* increase by the end of the 21st century under RCP8.5 (*medium confidence*). In contrast, water resources are projected to increase at high latitudes (*robust evidence, high agreement*). Climate change is projected to reduce raw water quality and pose risks to drinking water quality even with conventional treatment, due to interacting factors: increased temperature; increased sediment, nutrient, and pollutant loadings from heavy rainfall; increased concentration of pollutants during droughts; and disruption of treatment facilities during floods (*medium evidence, high agreement*). [3.2, 3.4, 3.5, 22.3, 23.9, 25.5, 26.3, Tables 3-2 and 23-3, Boxes CC-RF and CC-WE; WGI AR5 12.4]

Adaptive water management techniques, including scenario planning, learning-based approaches, and flexible and low-regret solutions, can help create resilience to uncertain hydrological changes and impacts due to climate change (*limited evidence, high agreement*). Barriers to progress include lack of human and institutional capacity, financial resources, awareness, and communication. [3.6, Box 25-2]

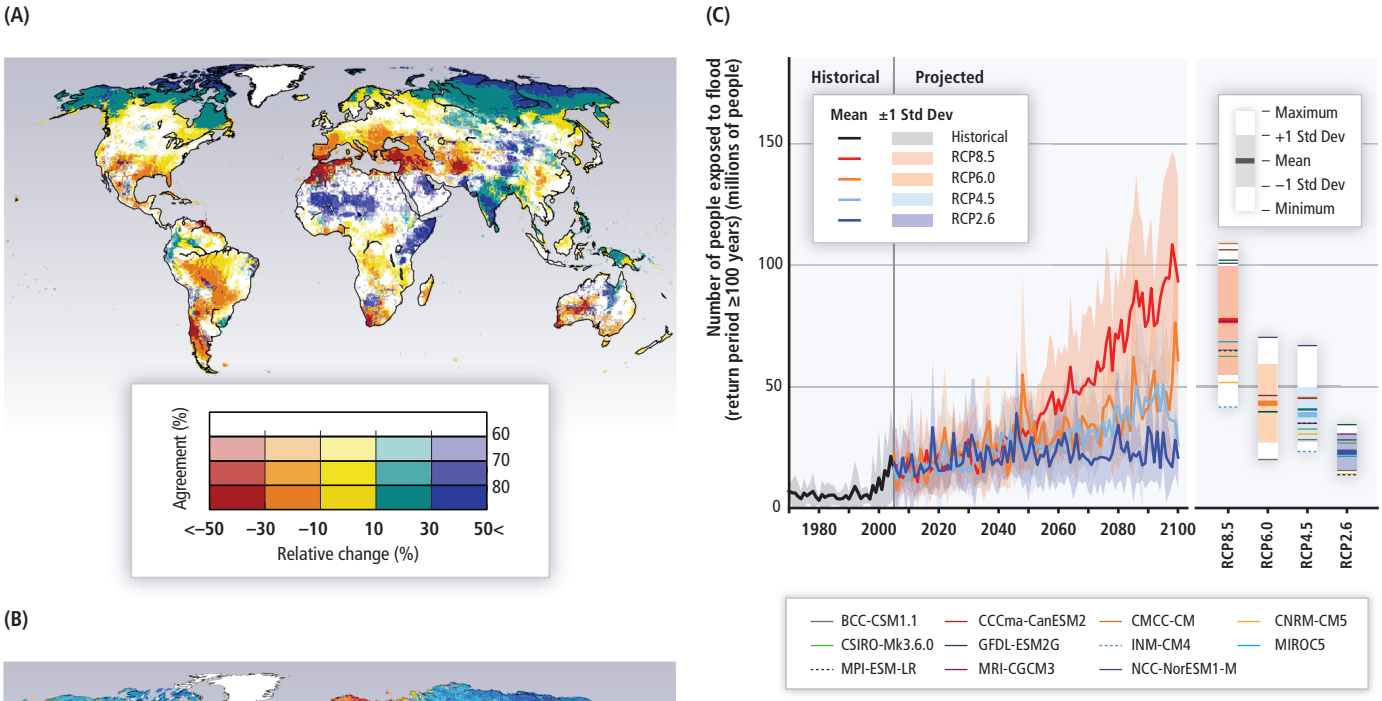


Figure TS.6 | (A) Percentage change of mean annual streamflow for a global mean temperature rise of 2°C above 1980–2010. Color hues show the multi-model mean change across 5 General Circulation Models (GCMs) and 11 Global Hydrological Models (GHMs), and saturation shows the agreement on the sign of change across all 55 GHM–GCM combinations (percentage of model runs agreeing on the sign of change). (B and C) Projected change in river flood return period and exposure, based on one hydrological model driven by 11 GCMs and on global population in 2005. (B) In the 2080s under RCP8.5, multi-model median return period (years) for the 20th-century 100-year flood. (C) Global exposure to the 20th-century 100-year flood in millions of people. Left: Ensemble means of historical (black line) and future simulations (colored lines) for each scenario. Shading denotes ±1 standard deviation. Right: Maximum and minimum (extent of white), mean (thick colored lines), ±1 standard deviation (extent of shading), and projections of each GCM (thin colored lines) averaged over the 21st century. [Figures 3-4 and 3-6]

Terrestrial and Freshwater Ecosystems

Climate change is projected to be a powerful stressor on terrestrial and freshwater ecosystems in the second half of the 21st century, especially under high-warming scenarios such as RCP6.0 and 8.5 (*high confidence*). Through to 2040 globally, direct human impacts such as land-use change, pollution, and water resource development will continue to dominate threats to most freshwater ecosystems (*high confidence*) and most terrestrial ecosystems (*medium confidence*). Many species will be unable to track suitable climates under mid- and high-range rates of climate change (i.e., RCP4.5, 6.0, and 8.5) during the 21st century (*medium confidence*). Lower rates of change (i.e., RCP2.6) will pose fewer problems. See Figure TS.7. Some species will adapt to new climates. Those that cannot adapt sufficiently fast will decrease in abundance or go extinct in part or all of their ranges. Increased tree mortality and associated forest dieback is projected to occur in many regions over the 21st century, due to increased temperatures and drought (*medium confidence*). Forest dieback poses risks for carbon storage, biodiversity, wood production, water quality, amenity, and economic activity. Management actions, such as maintenance of genetic diversity, assisted species migration and dispersal, manipulation of disturbance regimes (e.g., fires, floods), and reduction of other stressors, can reduce, but not eliminate, risks of impacts to terrestrial and freshwater ecosystems due to climate change, as well as increase the inherent capacity of ecosystems and their species to adapt to a changing climate (*high confidence*). [4.3, 4.4, 25.6, 26.4, Boxes 4-2, 4-3, and CC-RF]

A large fraction of both terrestrial and freshwater species faces increased extinction risk under projected climate change during and beyond the 21st century, especially as climate change interacts with other stressors, such as habitat modification, over-exploitation, pollution, and invasive species (*high confidence*). Extinction risk is increased under all RCP scenarios, with risk increasing with both magnitude and rate of climate change. Models project that the risk of species extinctions will increase in the future due to climate change, but there is *low agreement* concerning the fraction of species at increased risk, the regional and taxonomic distribution of such extinctions, and the timeframe over which extinctions could occur. Some aspects leading to uncertainty in the quantitative projections of extinction risks were not taken into account in previous models; as more realistic details are included, it has been shown that the extinction risks may be either under- or overestimated when based on simpler models. [4.3, 25.6]

Within this century, magnitudes and rates of climate change associated with medium- to high-emission scenarios (RCP4.5, 6.0, and 8.5) pose high risk of abrupt and irreversible regional-scale change in the composition, structure, and function of

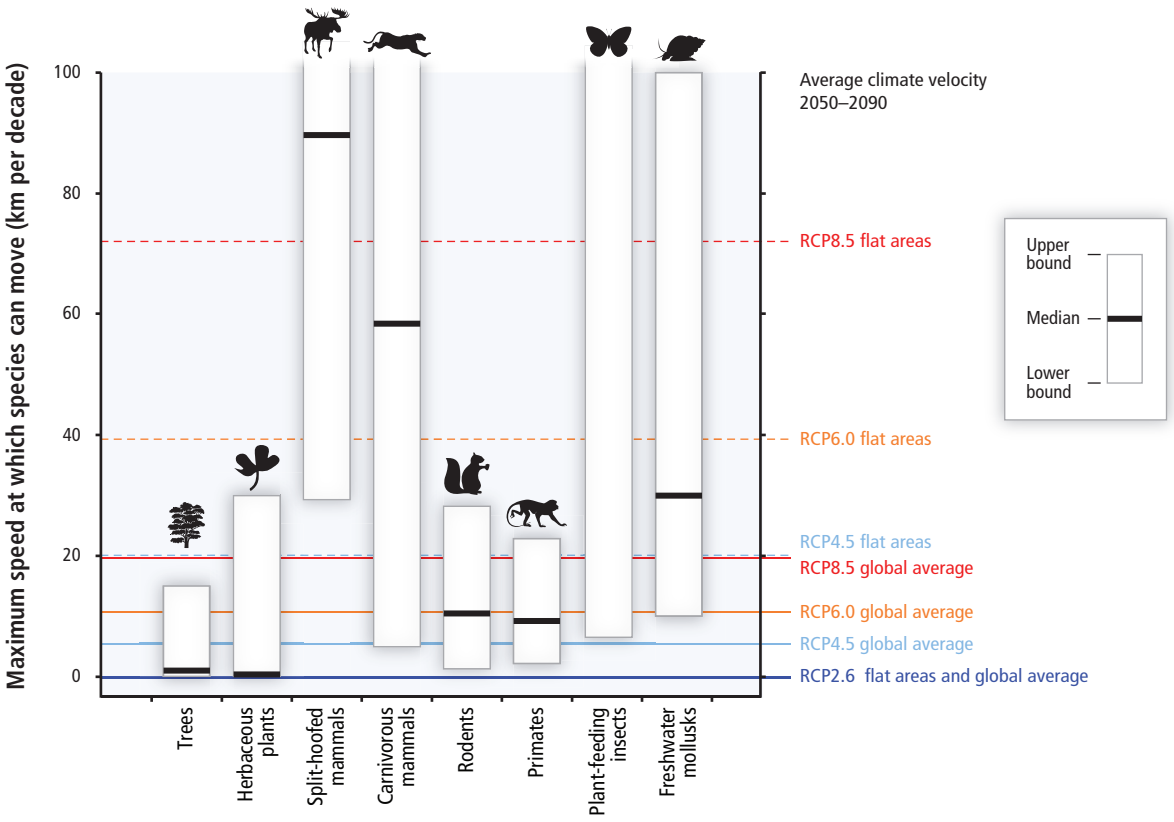


Figure TS.7 | Maximum speeds at which species can move across landscapes (based on observations and models; vertical axis on left), compared with speeds at which temperatures are projected to move across landscapes (climate velocities for temperature; vertical axis on right). Human interventions, such as transport or habitat fragmentation, can greatly increase or decrease speeds of movement. White boxes with black bars indicate ranges and medians of maximum movement speeds for trees, plants, mammals, plant-feeding insects (median not estimated), and freshwater mollusks. For RCP2.6, 4.5, 6.0, and 8.5 for 2050–2090, horizontal lines show climate velocity for the global-land-area average and for large flat regions. Species with maximum speeds below each line are expected to be unable to track warming in the absence of human intervention. [Figure 4-5]

terrestrial and freshwater ecosystems, including wetlands (*medium confidence*). Examples that could lead to substantial impact on climate are the boreal–tundra Arctic system (*medium confidence*) and the Amazon forest (*low confidence*). For the boreal–tundra system, continued climate change will transform the species composition, land cover, drainage, and permafrost extent of the boreal–tundra system, leading to decreased albedo and the release of greenhouse gases (*medium confidence*), with adaptation measures unable to prevent substantial change (*high confidence*). Increased severe drought together with land-use change and forest fire would cause much of the Amazon forest to transform to less-dense drought- and fire-adapted ecosystems, increasing risk for biodiversity while decreasing net carbon uptake from the atmosphere (*low confidence*). Large reductions in deforestation, as well as wider application of effective wildfire management, will lower the risk of abrupt change in the Amazon, as well as potential negative impacts of that change (*medium confidence*). [4.2, 4.3, Figure 4-8, Boxes 4-3 and 4-4]

The natural carbon sink provided by terrestrial ecosystems is partially offset at the decadal timescale by carbon released through the conversion of natural ecosystems (principally forests) to farm and grazing land and through ecosystem degradation (*high confidence*). Carbon stored in the terrestrial biosphere (e.g., in peatlands, permafrost, and forests) is susceptible to loss to the atmosphere as a result of climate change, deforestation, and ecosystem degradation. [4.2, 4.3, Box 4-3]

Coastal Systems and Low-lying Areas

Due to sea level rise projected throughout the 21st century and beyond, coastal systems and low-lying areas will increasingly experience adverse impacts such as submergence, coastal flooding, and coastal erosion (*very high confidence*). The population and assets projected to be exposed to coastal risks as well as human pressures on coastal ecosystems will increase significantly in the coming decades due to population growth, economic development, and urbanization (*high confidence*). The relative costs of coastal adaptation vary strongly among and within regions and countries for the 21st century. Some low-lying developing countries and small island states are expected to face very high impacts that, in some cases, could have associated damage and adaptation costs of several percentage points of GDP. [5.3 to 5.5, 8.2, 22.3, 24.4, 25.6, 26.3, 26.8, Table 26-1, Box 25-1]

Marine Systems

By mid 21st century, spatial shifts of marine species will cause species richness and fisheries catch potential to increase, on average, at mid and high latitudes (*high confidence*) and to decrease at tropical latitudes (*medium confidence*), resulting in global redistribution of catch potential for fishes and invertebrates, with implications for food security (*medium confidence*). Spatial shifts of marine species due to projected warming will cause high-latitude invasions and high local-extinction rates in the tropics and semi-enclosed seas (*medium confidence*). Animal displacements will cause a 30 to 70% increase in the fisheries yield of some high-latitude regions by 2055 (relative to 2005), a redistribution at mid latitudes, and a drop of 40 to 60% in some of the tropics and the Antarctic, for 2°C warming above preindustrial levels (*medium confidence* for direction of fisheries' yield trends, *low confidence* for the precise magnitudes of yield change). See Figure TS.8A. The progressive expansion of oxygen minimum zones and anoxic "dead zones" is projected to further constrain the habitat of fishes and other O_2-dependent organisms (*medium confidence*). Open-ocean net primary production is projected to redistribute and, by 2100, fall globally under all RCP scenarios. [6.3 to 6.5, 7.4, 25.6, 28.3, 30.4 to 30.6, Boxes CC-MB and CC-PP]

Due to projected climate change by the mid 21st century and beyond, global marine-species redistribution and marine-biodiversity reduction in sensitive regions will challenge the sustained provision of fisheries productivity and other ecosystem goods and services (*high confidence*). Socioeconomic vulnerability is highest in developing tropical countries, leading to risks from reduced supplies, income, and employment from marine fisheries. [6.4, 6.5]

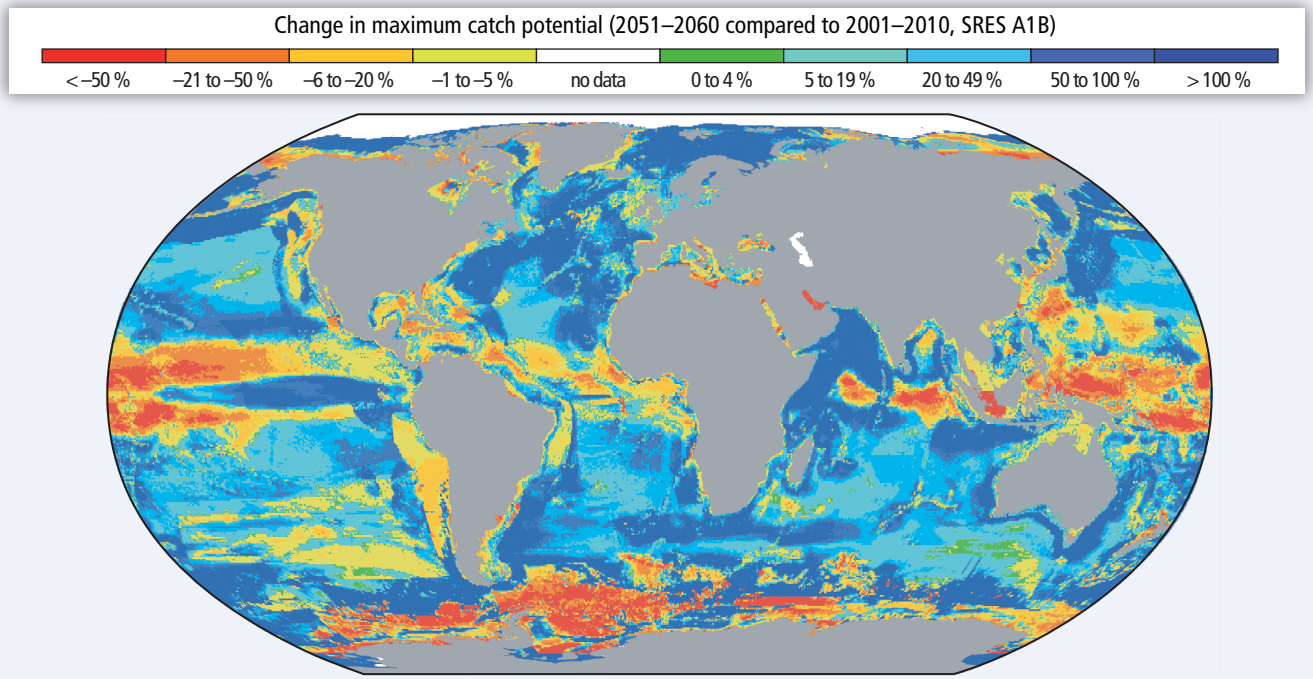
For medium- to high-emission scenarios (RCP4.5, 6.0, and 8.5), ocean acidification poses substantial risks to marine ecosystems, especially polar ecosystems and coral reefs, associated with impacts on the physiology, behavior, and population dynamics of individual species from phytoplankton to animals (*medium* to *high confidence*). See Box TS.7. Highly calcified mollusks, echinoderms, and reef-building corals are more sensitive than crustaceans (*high confidence*) and fishes (*low confidence*), with potentially detrimental consequences for fisheries and livelihoods (Figure TS.8B). Ocean acidification acts together with other global changes (e.g., warming, decreasing oxygen levels) and with local changes (e.g., pollution, eutrophication) (*high confidence*). Simultaneous drivers, such as warming and ocean acidification, can lead to interactive, complex, and amplified impacts for species and ecosystems. [5.4, 6.3 to 6.5, 22.3, 25.6, 28.3, 30.5, Boxes CC-CR and CC-OA]

Climate change adds to the threats of over-fishing and other non-climatic stressors, thus complicating marine management regimes (*high confidence*). In the short term, strategies including climate forecasting and early warning systems can reduce risks from ocean warming and acidification for some fisheries and aquaculture industries. Fisheries and aquaculture industries with high-technology

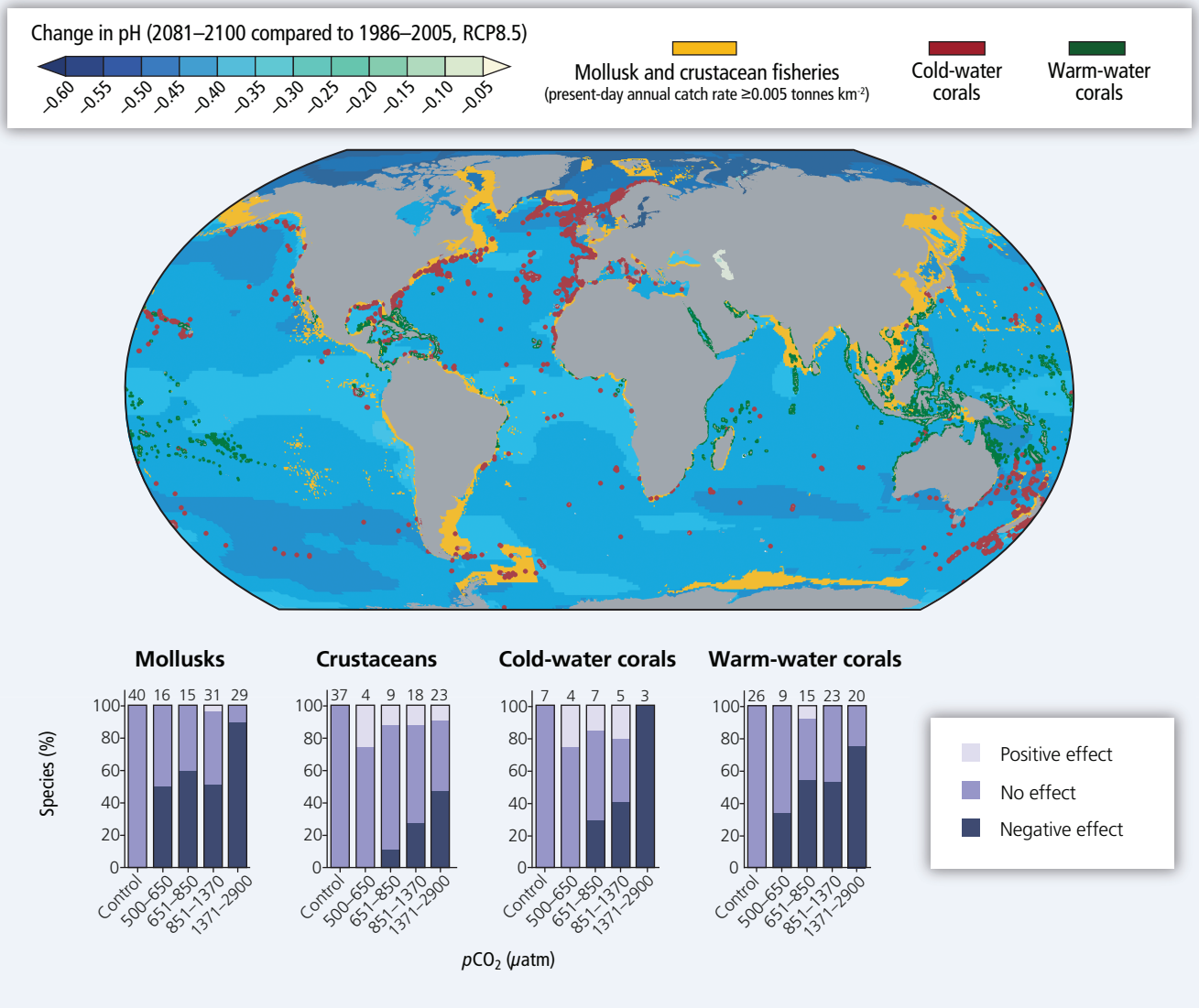
→

Figure TS.8 | Climate change risks for fisheries. (A) Projected global redistribution of maximum catch potential of ~1000 exploited fish and invertebrate species. Projections compare the 10-year averages 2001–2010 and 2051–2060 using SRES A1B, without analysis of potential impacts of overfishing or ocean acidification. (B) Marine mollusk and crustacean fisheries (present-day estimated annual catch rates ≥0.005 tonnes km^{-2}) and known locations of cold- and warm-water corals, depicted on a global map showing the projected distribution of ocean acidification under RCP8.5 (pH change from 1986–2005 to 2081–2100). [WGI AR5 Figure SPM.8] The bottom panel compares sensitivity to ocean acidification across mollusks, crustaceans, and corals, vulnerable animal phyla with socioeconomic relevance (e.g., for coastal protection and fisheries). The number of species analyzed across studies is given for each category of elevated CO_2. For 2100, RCP scenarios falling within each CO_2 partial pressure (pCO_2) category are as follows: RCP4.5 for 500–650 μatm (approximately equivalent to ppm in the atmosphere), RCP6.0 for 651–850 μatm, and RCP8.5 for 851–1370 μatm. By 2150, RCP8.5 falls within the 1371–2900 μatm category. The control category corresponds to 380 μatm. [6.1, 6.3, 30.5, Figures 6-10 and 6-14; WGI AR5 Box SPM.1]

(A)


Change in maximum catch potential (2051–2060 compared to 2001–2010, SRES A1B)
< –50 %
–21 to –50 %
–6 to –20 %
–1 to –5 %
no data
0 to 4 %
5 to 19 %
20 to 49 %
50 to 100 %
> 100 %

(B)


Change in pH (2081–2100 compared to 1986–2005, RCP8.5)
–0.60
–0.55
–0.50
–0.45
–0.40
–0.35
–0.30
–0.25
–0.20
–0.15
–0.10
–0.05
Mollusk and crustacean fisheries
(present-day annual catch rate ≥0.005 tonnes km-2)
Cold-water corals
Warm-water corals
Mollusks
Crustaceans
Cold-water corals
Warm-water corals
Species (%)
40 16 15 31 29
37 4 9 18 23
7 4 7 5 3
26 9 15 23 20
Control
500–650
651–850
851–1370
1371–2900
pCO2 (μatm)
Positive effect
No effect
Negative effect

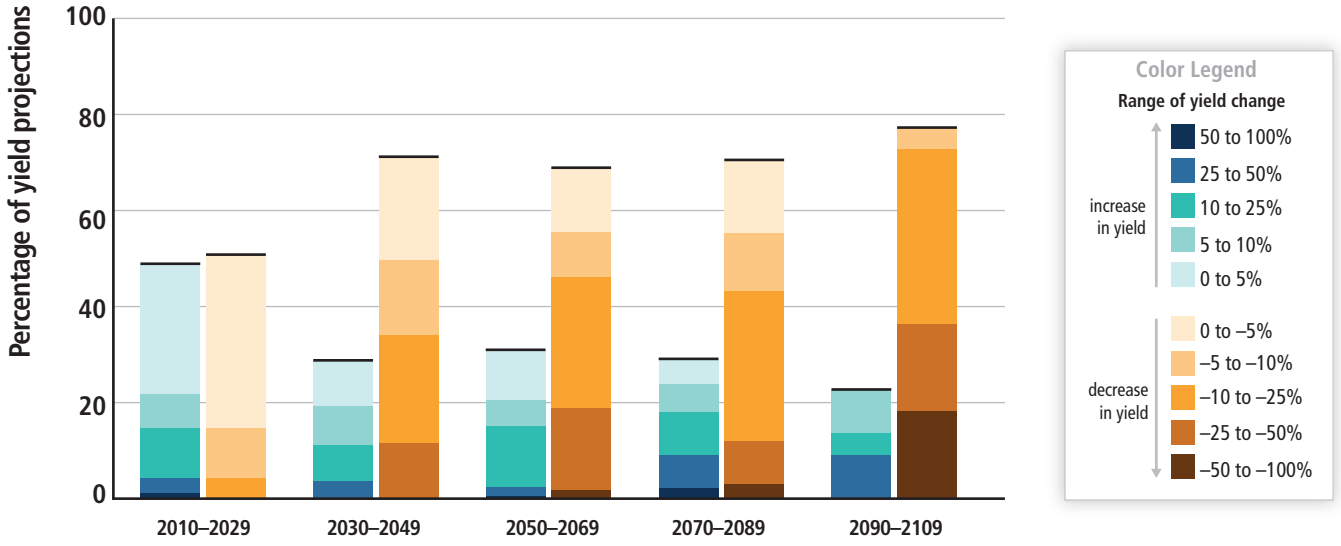


Figure TS.9 | Summary of projected changes in crop yields, due to climate change over the 21st century. The figure includes projections for different emission scenarios, for tropical and temperate regions, and for adaptation and no-adaptation cases combined. Relatively few studies have considered impacts on cropping systems for scenarios where global mean temperatures increase by 4°C or more. For five timeframes in the near term and long term, data (n=1090) are plotted in the 20-year period on the horizontal axis that includes the midpoint of each future projection period. Changes in crop yields are relative to late-20th-century levels. Data for each timeframe sum to 100%. [Figure 7-5]

and/or large investments, as well as marine shipping and oil and gas industries, have high capacities for adaptation due to greater development of environmental monitoring, modeling, and resource assessments. For smaller-scale fisheries and developing countries, building social resilience, alternative livelihoods, and occupational flexibility represent important strategies for reducing the vulnerability of ocean-dependent human communities. [6.4, 7.3, 7.4, 25.6, 29.4, 30.6, 30.7]

Food Security and Food Production Systems

For the major crops (wheat, rice, and maize) in tropical and temperate regions, climate change without adaptation is projected to negatively impact aggregate production for local temperature increases of 2°C or more above late-20th-century levels, although individual locations may benefit (*medium confidence*). Projected impacts vary across crops and regions and adaptation scenarios, with about 10% of projections for the period 2030–2049 showing yield gains of more than 10%, and about 10% of projections showing yield losses of more than 25%, compared to the late 20th century. After 2050 the risk of more severe yield impacts increases and depends on the level of warming. See Figure TS.9. Climate change is projected to progressively increase inter-annual variability of crop yields in many regions. These projected impacts will occur in the context of rapidly rising crop demand. [7.4, 7.5, 22.3, 24.4, 25.7, 26.5, Table 7-2, Figures 7-4, 7-5, 7-6, 7-7, and 7-8]

All aspects of food security are potentially affected by climate change, including food access, utilization, and price stability (*high confidence*). Redistribution of marine fisheries catch potential towards higher latitudes poses risk of reduced supplies, income, and employment in tropical countries, with potential implications for food security (*medium confidence*). Global temperature increases of ~4°C or more above late-20th-century levels, combined with increasing food demand, would pose large risks to food security globally and regionally (*high confidence*). Risks to food security are generally greater in low-latitude areas. [6.3 to 6.5, 7.4, 7.5, 9.3, 22.3, 24.4, 25.7, 26.5, Table 7-3, Figures 7-1, 7-4, and 7-7, Box 7-1]

Urban Areas

Many global risks of climate change are concentrated in urban areas (*medium confidence*). Steps that build resilience and enable sustainable development can accelerate successful climate-change adaptation globally. Heat stress, extreme precipitation, inland and coastal flooding, landslides, air pollution, drought, and water scarcity pose risks in urban areas for people, assets, economies, and ecosystems (*very high confidence*). Risks are amplified for those lacking essential infrastructure and services or living in poor-quality housing and exposed areas. Reducing basic service deficits, improving housing, and building resilient infrastructure systems could significantly reduce vulnerability and exposure in urban areas. Urban adaptation benefits from effective multi-level urban risk governance, alignment of policies and incentives, strengthened local government and community adaptation capacity, synergies with the private sector, and appropriate financing and institutional development (*medium confidence*). Increased capacity, voice, and influence of low-income groups and vulnerable communities and their partnerships with local governments also benefit adaptation. [3.5, 8.2 to 8.4, 22.3, 24.4, 24.5, 26.8, Table 8-2, Boxes 25-9 and CC-HS]

Rural Areas

Major future rural impacts are expected in the near term and beyond through impacts on water availability and supply, food security, and agricultural incomes, including shifts in production areas of food and non-food crops across the world (*high*

***confidence*).** These impacts are expected to disproportionately affect the welfare of the poor in rural areas, such as female-headed households and those with limited access to land, modern agricultural inputs, infrastructure, and education. Climate change will increase international agricultural trade volumes in both physical and value terms (*limited evidence*, *medium agreement*). Importing food can help countries adjust to climate change-induced domestic productivity shocks while short-term food deficits in developing countries with low income may have to be met through food aid. Further adaptations for agriculture, water, forestry, and biodiversity can occur through policies taking account of rural decision-making contexts. Trade reform and investment can improve market access for small-scale farms (*medium confidence*). Valuation of non-marketed ecosystem services and limitations of economic valuation models that aggregate across contexts pose challenges for valuing rural impacts. [9.3, 25.9, 26.8, 28.2, 28.4, Box 25-5]

Key Economic Sectors and Services

For most economic sectors, the impacts of drivers such as changes in population, age structure, income, technology, relative prices, lifestyle, regulation, and governance are projected to be large relative to the impacts of climate change (*medium evidence*, *high agreement*). Climate change is projected to reduce energy demand for heating and increase energy demand for cooling in the residential and commercial sectors (*robust evidence*, *high agreement*). Climate change is projected to affect energy sources and technologies differently, depending on resources (e.g., water flow, wind, insolation), technological processes (e.g., cooling), or locations (e.g., coastal regions, floodplains) involved. More severe and/or frequent extreme weather events and/or hazard types are projected to increase losses and loss variability in various regions and challenge insurance systems to offer affordable coverage while raising more risk-based capital, particularly in developing countries. Large-scale public-private risk reduction initiatives and economic diversification are examples of adaptation actions. [3.5, 10.2, 10.7, 10.10, 17.4, 17.5, 25.7, 26.7 to 26.9, Box 25-7]

Climate change may influence the integrity and reliability of pipelines and electricity grids (*medium evidence*, *medium agreement*). Climate change may require changes in design standards for the construction and operation of pipelines and of power transmission and distribution lines. Adopting existing technology from other geographical and climatic conditions may reduce the cost of adapting new infrastructure as well as the cost of retrofitting existing pipelines and grids. Climate change may negatively affect transport infrastructure (*limited evidence*, *high agreement*). All infrastructure is vulnerable to freeze-thaw cycles; paved roads are particularly vulnerable to temperature extremes, unpaved roads and bridges to precipitation extremes. Transport infrastructure on ice or permafrost is especially vulnerable. [10.2, 10.4, 25.7, 26.7]

Climate change will affect tourism resorts, particularly ski resorts, beach resorts, and nature resorts (*robust evidence*, *high agreement*), and tourists may spend their holidays at higher altitudes and latitudes (*medium evidence*, *high agreement*). The economic implications of climate-change-induced changes in tourism demand and supply entail gains for countries closer to the poles and countries with higher elevations and losses for other countries. [10.6, 25.7]

Global economic impacts from climate change are difficult to estimate. Economic impact estimates completed over the past 20 years vary in their coverage of subsets of economic sectors and depend on a large number of assumptions, many of which are disputable, and many estimates do not account for catastrophic changes, tipping points, and many other factors. With these recognized limitations, the incomplete estimates of global annual economic losses for additional temperature increases of ~2°C are between 0.2 and 2.0% of income (±1 standard deviation around the mean) (*medium evidence*, *medium agreement*). Losses are *more likely than not* to be greater, rather than smaller, than this range (*limited evidence*, *high agreement*). Additionally, there are large differences between and within countries. Losses accelerate with greater warming (*limited evidence*, *high agreement*), but few quantitative estimates have been completed for additional warming around 3°C or above. Estimates of the incremental economic impact of emitting carbon dioxide lie between a few dollars and several hundreds of dollars per tonne of carbon[3] (*robust evidence*, *medium agreement*). Estimates vary strongly with the assumed damage function and discount rate. [10.9]

Human Health

Until mid-century, projected climate change will impact human health mainly by exacerbating health problems that already exist (*very high confidence*). Throughout the 21st century, climate change is expected to lead to increases in ill-health in many regions and especially in developing countries with low income, as compared to a baseline without climate change (*high confidence*). Examples include greater likelihood of injury, disease, and death due to more intense heat waves and fires (*very high confidence*); increased likelihood of under-nutrition resulting from diminished food production in poor regions (*high confidence*); risks from lost work capacity and reduced labor productivity in vulnerable populations; and increased risks from food- and water-borne diseases (*very high confidence*) and vector-borne diseases (*medium confidence*). Impacts on health will be reduced, but not eliminated, in populations that benefit from rapid social and economic development, particularly among the poorest and least healthy groups (*high confidence*). Climate change will increase demands for health care services and facilities, including public health programs, disease prevention activities, health care personnel, infrastructure, and supplies for treatment (*medium evidence*, *high agreement*). Positive effects are expected to include modest reductions in cold-related mortality and morbidity in some areas due to fewer cold extremes (*low confidence*), geographical shifts in food production (*medium confidence*), and reduced capacity of vectors to transmit some diseases. But globally over the 21st century, the magnitude and severity of negative impacts are projected to increasingly outweigh positive impacts (*high confidence*). The most effective vulnerability reduction measures for health in the near term are programs that implement and improve basic public health measures such as provision of clean water and sanitation, secure essential health care including vaccination and child health services,

[3] 1 tonne of carbon = 3.667 tonne of CO_2

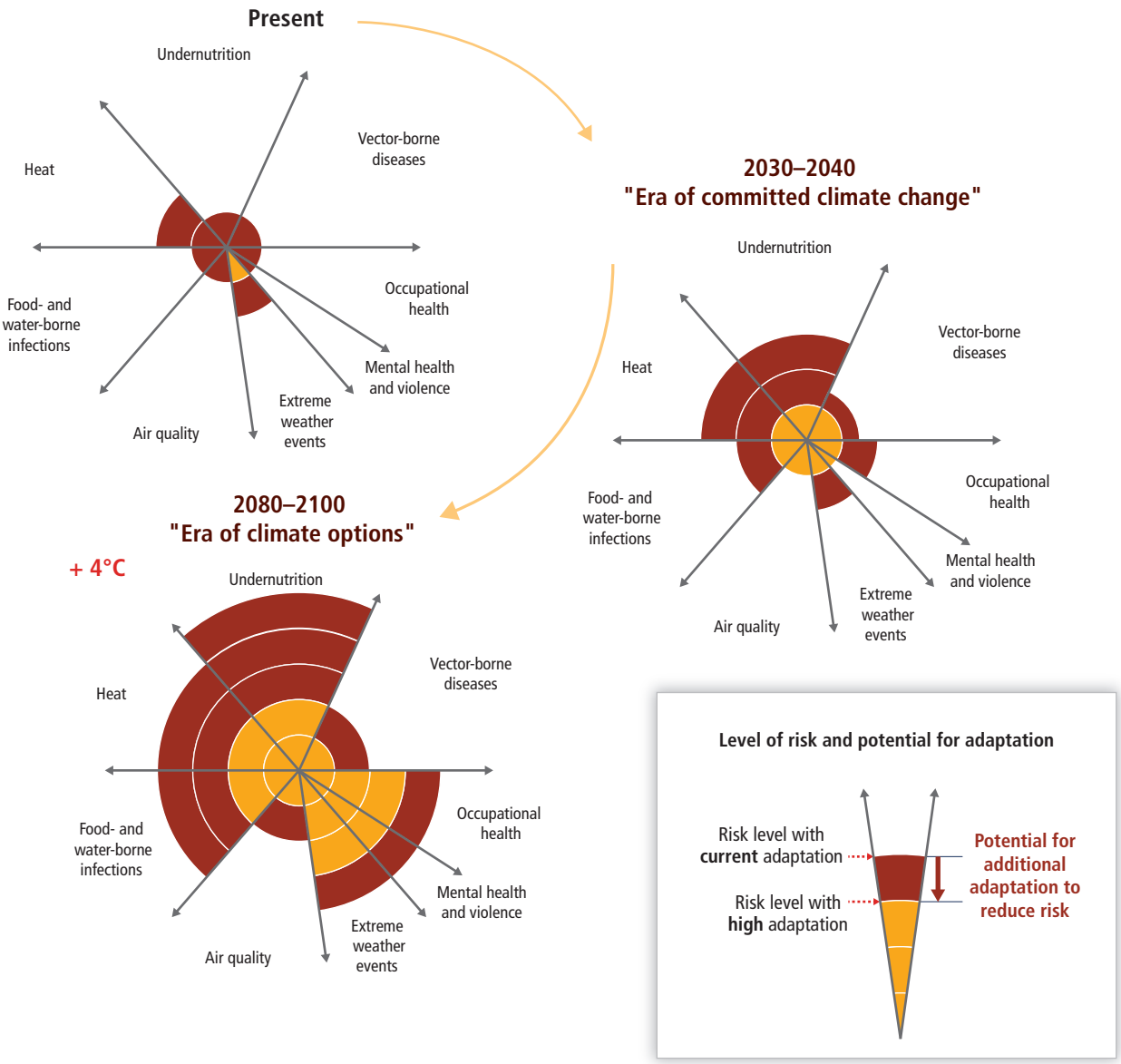


Figure TS.10 | Conceptual presentation of health risks from climate change and the potential for risk reduction through adaptation. Risks are identified in eight health-related categories based on assessment of the literature and expert judgments by authors of Chapter 11. The width of the slices indicates in a qualitative way relative importance in terms of burden of ill-health globally at present. Risk levels are assessed for the present and for the near-term era of committed climate change (here, for 2030–2040). For some categories, for example, vector-borne diseases, heat/cold stress, and agricultural production and undernutrition, there may be benefits to health in some areas, but the net impact is expected to be negative. Risk levels are also presented for the longer-term era of climate options (here, for 2080–2100) for global mean temperature increase of 4°C above preindustrial levels. For each timeframe, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state, indicated by different colors. [Figure 11-6]

increase capacity for disaster preparedness and response, and alleviate poverty (*very high confidence*). By 2100 for the high-emission scenario RCP8.5, the combination of high temperature and humidity in some areas for parts of the year is projected to compromise normal human activities, including growing food or working outdoors (*high confidence*). See Figure TS.10. [8.2, 11.3 to 11.8, 19.3, 22.3, 25.8, 26.6, Figure 25-5, Box CC-HS]

Human Security

Human security will be progressively threatened as the climate changes (*robust evidence, high agreement*). Human insecurity almost never has single causes, but instead emerges from the interaction of multiple factors. Climate change is an important factor in threats to human security through (1) undermining livelihoods, (2) compromising culture and identity, (3) increasing migration that people would rather have avoided, and (4) challenging the ability of states to provide the conditions necessary for human security. See Figure TS.11. [12.1 to 12.4, 12.6]

Climate change will compromise the cultural values that are important for community and individual well-being (*medium evidence, high agreement*). The effect of climate change on culture will vary across societies and over time, depending on cultural resilience and the mechanisms for maintaining and transferring knowledge. Changing weather and climatic conditions threaten cultural practices

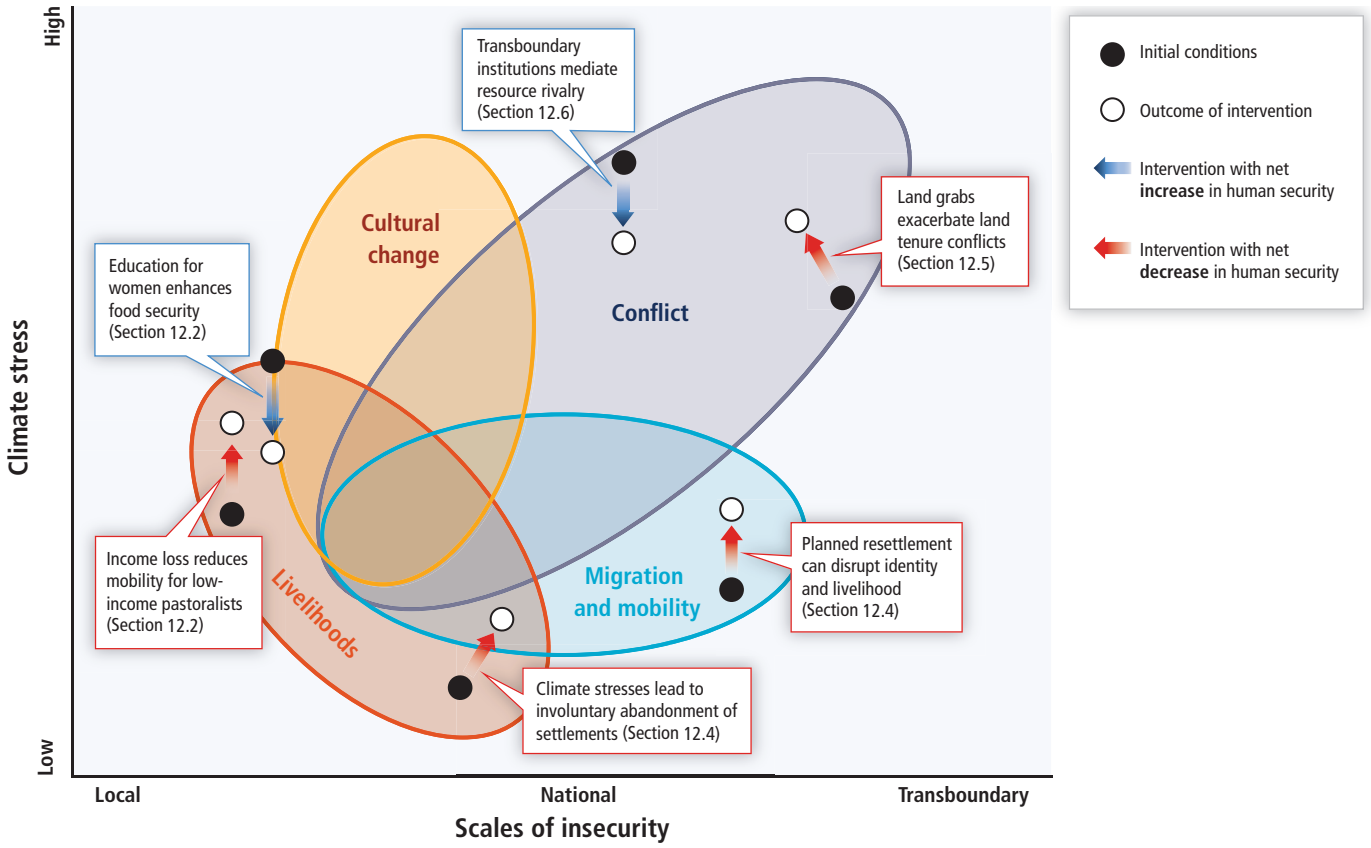


Figure TS.11 | Schematic of climate change risks for human security and the interactions between livelihoods, conflict, culture, and migration. Interventions and policies are indicated by the difference between initial conditions (solid black circles) and the outcome of intervention (white circles). Some interventions (blue arrows) show net increase in human security while others (red arrows) lead to net decrease in human security. [Figure 12-3]

embedded in livelihoods and expressed in narratives, worldviews, identity, community cohesion, and sense of place. Loss of land and displacement, for example, on small islands and coastal communities, have well documented negative cultural and well-being impacts. [12.3, 12.4]

Climate change over the 21st century is projected to increase displacement of people (*medium evidence*, *high agreement*). Displacement risk increases when populations that lack the resources for planned migration experience higher exposure to extreme weather events, in both rural and urban areas, particularly in developing countries with low income. Expanding opportunities for mobility can reduce vulnerability for such populations. Changes in migration patterns can be responses to both extreme weather events and longer-term climate variability and change, and migration can also be an effective adaptation strategy. There is *low confidence* in quantitative projections of changes in mobility, due to its complex, multi-causal nature. [9.3, 12.4, 19.4, 22.3, 25.9]

Climate change can indirectly increase risks of violent conflicts in the form of civil war and inter-group violence by amplifying well-documented drivers of these conflicts such as poverty and economic shocks (*medium confidence*). Multiple lines of evidence relate climate variability to these forms of conflict. [12.5, 13.2, 19.4]

The impacts of climate change on the critical infrastructure and territorial integrity of many states are expected to influence national security policies (*medium evidence*, *medium agreement*). For example, land inundation due to sea level rise poses risks to the territorial integrity of small island states and states with extensive coastlines. Some transboundary impacts of climate change, such as changes in sea ice, shared water resources, and pelagic fish stocks, have the potential to increase rivalry among states, but robust national and intergovernmental institutions can enhance cooperation and manage many of these rivalries. [12.5, 12.6, 23.9, 25.9]

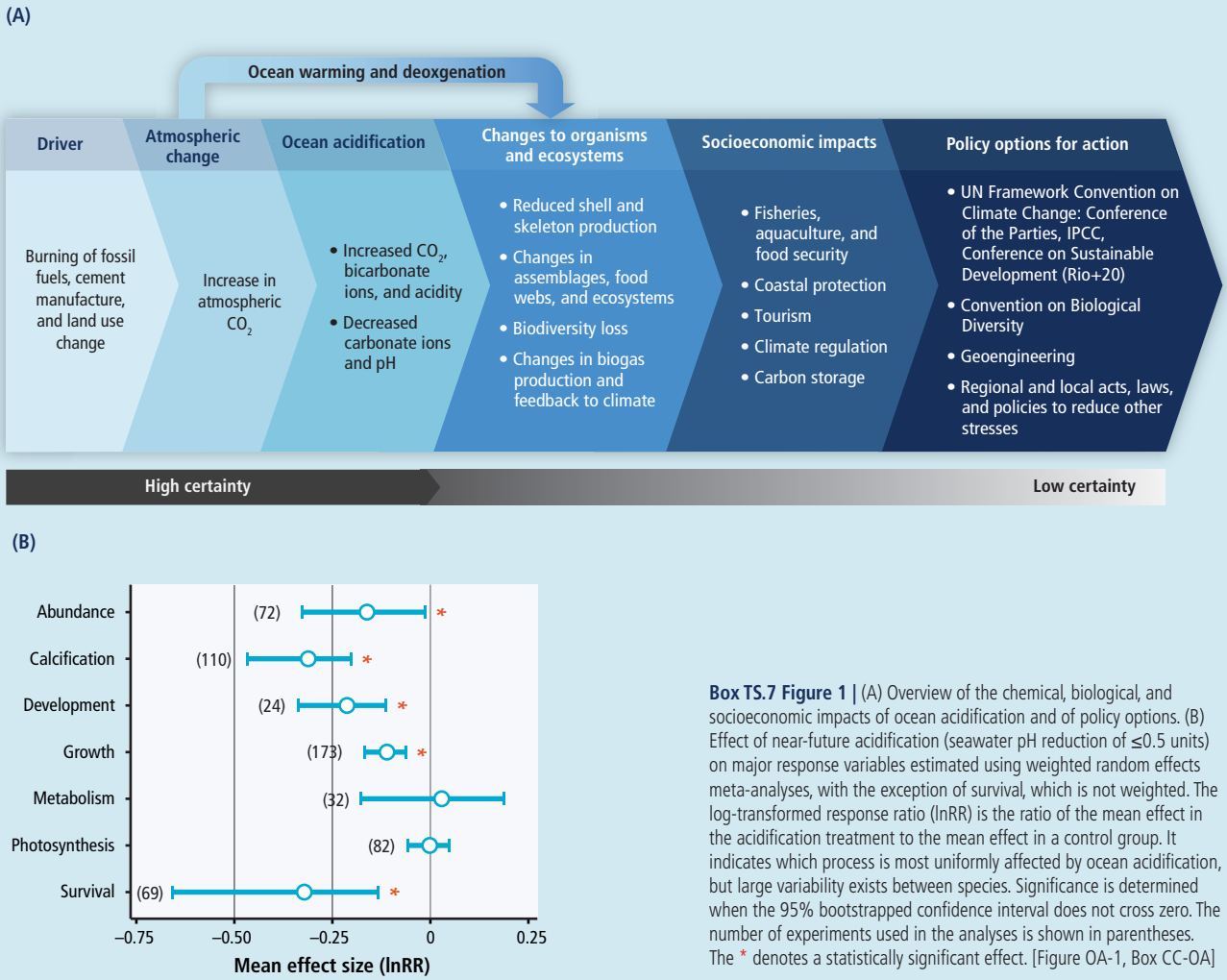
Livelihoods and Poverty

Throughout the 21st century, climate-change impacts are projected to slow down economic growth, make poverty reduction more difficult, further erode food security, and prolong existing and create new poverty traps, the latter particularly in urban areas and emerging hotspots of hunger (*medium confidence*). Climate-change impacts are expected to exacerbate poverty in most developing countries and create new poverty pockets in countries with increasing inequality, in both developed and developing countries. In urban and rural areas, wage-labor-dependent poor households that are net buyers of food are expected to be particularly affected due to food price increases, including in regions with high food insecurity and high inequality (particularly in Africa), although the agricultural self-employed could benefit. Insurance programs, social protection measures, and disaster risk management may enhance long-term livelihood resilience

Box TS.7 | Ocean Acidification

Anthropogenic ocean acidification and global warming share the same primary cause, which is the increase of atmospheric CO_2 (Box TS.7 Figure 1A). [WGI AR5 2.2] Eutrophication, upwelling, and deposition of atmospheric nitrogen and sulfur contribute to ocean acidification locally. [5.3, 6.1, 30.3] The fundamental chemistry of ocean acidification is well understood (*robust evidence*, *high agreement*). [30.3; WGI AR5 3.8, 6.4] It has been more difficult to understand and project changes within the more complex coastal systems. [5.3, 30.3]

Ocean acidification acts together with other global changes (e.g., warming, decreasing oxygen levels) and with local changes (e.g., pollution, eutrophication) (*high confidence*). Simultaneous drivers, such as warming and ocean acidification, can lead to interactive, complex, and amplified impacts for species and ecosystems. A pattern of positive and negative impacts of ocean acidification emerges for processes and organisms (*high confidence*; Box TS.7 Figure 1B), but key uncertainties remain from organismal to ecosystem levels. A wide range of sensitivities exists within and across organisms, with higher sensitivity in early life stages. [6.3] Lower pH decreases the rate of calcification of most, but not all, sea floor calcifiers, reducing their competitiveness with non-calcifiers (*robust evidence*, *medium agreement*). [5.4, 6.3] Ocean acidification stimulates dissolution of calcium carbonate (*very high confidence*). Growth and primary production are stimulated in seagrasses and some phytoplankton (*high confidence*), and harmful algal blooms could become more frequent (*limited evidence*, *medium agreement*). Serious behavioral disturbances have been reported in fishes



Box TS.7 Figure 1 | (A) Overview of the chemical, biological, and socioeconomic impacts of ocean acidification and of policy options. (B) Effect of near-future acidification (seawater pH reduction of ≤0.5 units) on major response variables estimated using weighted random effects meta-analyses, with the exception of survival, which is not weighted. The log-transformed response ratio (lnRR) is the ratio of the mean effect in the acidification treatment to the mean effect in a control group. It indicates which process is most uniformly affected by ocean acidification, but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. The * denotes a statistically significant effect. [Figure OA-1, Box CC-OA]

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Box TS.7 (continued)

(*high confidence*). [6.3] Natural analogs at CO_2 vents indicate decreased species diversity, biomass, and trophic complexity. Shifts in organisms' performance and distribution will change both predator-prey and competitive interactions, which could impact food webs and higher trophic levels (*limited evidence*, *high agreement*). [6.3]

A few studies provide *limited evidence* for adaptation in phytoplankton and mollusks. However, mass extinctions in Earth history occurred during much slower rates of change in ocean acidification, combined with other drivers, suggesting that evolutionary rates may be too slow for sensitive and long-lived species to adapt to the projected rates of future change (*medium confidence*). [6.1]

The biological, ecological, and biogeochemical changes driven by ocean acidification will affect key ecosystem services. The oceans will become less efficient at absorbing CO_2 and hence moderating climate (*very high confidence*). [WGI AR5 Figure 6.26] The impacts of ocean acidification on coral reefs, together with those of thermal stress (driving mass coral bleaching and mortality) and sea level rise, will diminish their role in shoreline protection as well as their direct and indirect benefits to fishing and tourism industries (*limited evidence*, *high agreement*). [Box CC-CR] The global cost of production loss of mollusks could be over US$100 billion by 2100 (*low confidence*). The largest uncertainty is how the impacts on lower trophic levels will propagate through the food webs and to top predators. Models suggest that ocean acidification will generally reduce fish biomass and catch (*low confidence*) and complex additive, antagonistic, and/or synergistic interactions will occur with disruptive ramifications for ecosystems as well as for important ecosystem goods and services.

among poor and marginalized people, if policies address poverty and multidimensional inequalities. [8.1, 8.3, 8.4, 9.3, 10.9, 13.2 to 13.4, 22.3, 26.8]

B-3. Regional Risks and Potential for Adaptation

Risks will vary through time across regions and populations, dependent on myriad factors including the extent of adaptation and mitigation. A selection of key regional risks identified with *medium* to *high confidence* is presented in Table TS.5. Projected changes in climate and increasing atmospheric CO_2 will have positive effects for some sectors in some locations. For extended summary of regional risks and the more limited potential benefits, see introductory overviews for each region below and also WGII AR5 Part B: Regional Aspects, Chapters 21 to 30.

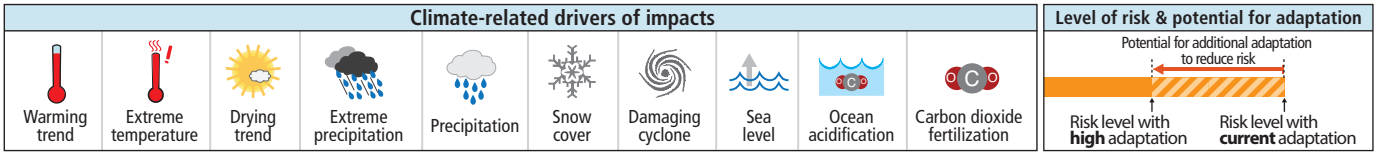
***Africa*. Climate change will amplify existing stress on water availability and on agricultural systems particularly in semi-arid environments (*high confidence*).** Increasing temperatures and changes in precipitation are *very likely* to reduce cereal crop productivity with strong adverse effects on food security (*high confidence*). Progress has been achieved on managing risks to food production from current climate variability and near-term climate change, but this will not be sufficient to address long-term impacts of climate change. Adaptive agricultural processes such as collaborative, participatory research that includes scientists and farmers, strengthened communication systems for anticipating and responding to climate risks, and increased flexibility in livelihood options provide potential pathways for strengthening adaptive capacities. Climate change is a multiplier of existing health vulnerabilities including insufficient access to safe water and improved sanitation, food insecurity, and limited access to health care and education. Strategies that integrate consideration of climate change risks with land and water management and disaster risk reduction bolster resilient development. [22.3 to 22.4, 22.6]

***Europe*. Climate change will increase the likelihood of systemic failures across European countries caused by extreme climate events affecting multiple sectors (*medium confidence*).** Sea level rise and increases in extreme rainfall are projected to further increase coastal and river flood risks and without adaptive measures will substantially increase flood damages (i.e., people affected and economic losses); adaptation can prevent most of the projected damages (*high confidence*). Heat-related deaths and injuries are *likely* to increase, particularly in southern Europe (*medium confidence*). Climate change is *likely* to increase cereal crop yields in northern Europe (*medium confidence*) but decrease yields in southern Europe (*high confidence*). Climate change will increase irrigation needs in Europe, and future irrigation will be constrained by reduced runoff, demand from other sectors, and economic costs, with integrated water management a strategy for addressing competing demands. Hydropower production is *likely* to decrease in all sub-regions except Scandinavia. Climate change is *very likely* to cause changes in habitats and species, with local extinctions (*high confidence*), continental-scale shifts in species distributions (*medium confidence*), and significantly reduced alpine plant habitat (*high confidence*). Climate change is *likely* to entail the loss or displacement of coastal wetlands. The introduction and expansion of invasive species, especially those with high migration rates, from outside Europe is *likely* to increase with climate change (medium confidence). [23.2 to 23.9]

***Asia*. Climate change will cause declines in agricultural productivity in many sub-regions of Asia, for crops such as rice (*medium confidence*).** In Central Asia, cereal production in northern and eastern Kazakhstan could benefit from the longer growing season, warmer winters, and slight increase in winter precipitation, while droughts in western Turkmenistan and Uzbekistan could negatively affect cotton production, increase water demand for irrigation, and exacerbate desertification. The effectiveness of potential and practiced agricultural adaptation strategies is not well understood. Future projections of precipitation at sub-regional scales and thus of freshwater availability in most parts of Asia are uncertain (*low confidence* in projections), but increased water demand from population growth, increased water consumption per capita, and lack of good management will increase water scarcity challenges for most of the region (*medium confidence*). Adaptive responses include integrated water management strategies, such as development of water-saving technologies, increased water productivity, and water reuse. Extreme climate events will have an increasing impact on human health, security, livelihoods, and poverty, with the type and magnitude of impact varying across Asia (*high confidence*). In many parts of Asia, observed terrestrial impacts, such as permafrost degradation and shifts in plant species' distributions, growth rates, and timing of seasonal activities, will increase due to climate change projected during the 21st century. Coastal and marine systems in Asia, such as mangroves, seagrass beds, salt marshes, and coral reefs, are under increasing stress from climatic and non-climatic drivers. In the Asian Arctic, sea level rise interacting with projected changes in permafrost and the length of the ice-free season will increase rates of coastal erosion (*medium evidence*, *high agreement*). [24.4, 30.5]

***Australasia*. Without adaptation, further changes in climate, atmospheric carbon dioxide, and ocean acidity are projected to have substantial impacts on water resources, coastal ecosystems, infrastructure, health, agriculture, and biodiversity (*high confidence*).** Freshwater resources are projected to decline in far

Table TS.5 | Key regional risks from climate change and the potential for reducing risks through adaptation and mitigation. Key risks have been identified based on assessment of the relevant scientific, technical, and socioeconomic literature detailed in supporting chapter sections. Identification of key risks was based on expert judgment using the following specific criteria: large magnitude, high probability, or irreversibility of impacts; timing of impacts; persistent vulnerability or exposure contributing to risks; or limited potential to reduce risks through adaptation or mitigation. Each key risk is characterized as very low to very high for three timeframes: the present, near term (here, assessed over 2030–2040), and longer term (here, assessed over 2080–2100). The risk levels integrate probability and consequence over the widest possible range of potential outcomes, based on available literature. These potential outcomes result from the interaction of climate-related hazards, vulnerability, and exposure. Each risk level reflects total risk from climatic and non-climatic factors. For the near-term era of committed climate change, projected levels of global mean temperature increase do not diverge substantially for different emission scenarios. For the longer-term era of climate options, risk levels are presented for two scenarios of global mean temperature increase (2°C and 4°C above preindustrial levels). These scenarios illustrate the potential for mitigation and adaptation to reduce the risks related to climate change. For the present, risk levels were estimated for current adaptation and a hypothetical highly adapted state, identifying where current adaptation deficits exist. For the two future timeframes, risk levels were estimated for a continuation of current adaptation and for a highly adapted state, representing the potential for and limits to adaptation. Climate-related drivers of impacts are indicated by icons. Key risks and risk levels vary across regions and over time, given differing socioeconomic development pathways, vulnerability and exposure to hazards, adaptive capacity, and risk perceptions. Risk levels are not necessarily comparable, especially across regions, because the assessment considers potential impacts and adaptation in different physical, biological, and human systems across diverse contexts. This assessment of risks acknowledges the importance of differences in values and objectives in interpretation of the assessed risk levels.



Africa

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Compounded stress on water resources facing significant strain from overexploitation and degradation at present and increased demand in the future, with drought stress exacerbated in drought-prone regions of Africa (*high confidence*) [22.3, 22.4]	• Reducing non-climate stressors on water resources • Strengthening institutional capacities for demand management, groundwater assessment, integrated water-wastewater planning, and integrated land and water governance • Sustainable urban development		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high
Reduced crop productivity associated with heat and drought stress, with strong adverse effects on regional, national, and household livelihood and food security, also given increased pest and disease damage and flood impacts on food system infrastructure (*high confidence*) [22.3, 22.4]	• Technological adaptation responses (e.g., stress-tolerant crop varieties, irrigation, enhanced observation systems) • Enhancing smallholder access to credit and other critical production resources; Diversifying livelihoods • Strengthening institutions at local, national, and regional levels to support agriculture (including early warning systems) and gender-oriented policy • Agronomic adaptation responses (e.g., agroforestry, conservation agriculture)		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high
Changes in the incidence and geographic range of vector- and water-borne diseases due to changes in the mean and variability of temperature and precipitation, particularly along the edges of their distribution (*medium confidence*) [22.3]	• Achieving development goals, particularly improved access to safe water and improved sanitation, and enhancement of public health functions such as surveillance • Vulnerability mapping and early warning systems • Coordination across sectors • Sustainable urban development		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high

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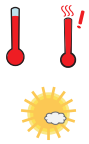
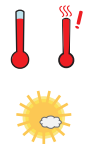
Europe				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Increased economic losses and people affected by flooding in river basins and coasts, driven by increasing urbanization, increasing sea levels, coastal erosion, and peak river discharges (*high confidence*) [23.2, 23.3, 23.7]	Adaptation can prevent most of the projected damages (*high confidence*). • Significant experience in hard flood-protection technologies and increasing experience with restoring wetlands • High costs for increasing flood protection • Potential barriers to implementation: demand for land in Europe and environmental and landscape concerns		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Increased water restrictions. Significant reduction in water availability from river abstraction and from groundwater resources, combined with increased water demand (e.g., for irrigation, energy and industry, domestic use) and with reduced water drainage and runoff as a result of increased evaporative demand, particularly in southern Europe (*high confidence*) [23.4, 23.7]	• Proven adaptation potential from adoption of more water-efficient technologies and of water-saving strategies (e.g., for irrigation, crop species, land cover, industries, domestic use) • Implementation of best practices and governance instruments in river basin management plans and integrated water management		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Increased economic losses and people affected by extreme heat events: impacts on health and well-being, labor productivity, crop production, air quality, and increasing risk of wildfires in southern Europe and in Russian boreal region (*medium confidence*) [23.3 to 23.7, Table 23-1]	• Implementation of warning systems • Adaptation of dwellings and workplaces and of transport and energy infrastructure • Reductions in emissions to improve air quality • Improved wildfire management • Development of insurance products against weather-related yield variations		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high

Asia				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Increased riverine, coastal, and urban flooding leading to widespread damage to infrastructure, livelihoods, and settlements in Asia (*medium confidence*) [24.4]	• Exposure reduction via structural and non-structural measures, effective land-use planning, and selective relocation • Reduction in the vulnerability of lifeline infrastructure and services (e.g., water, energy, waste management, food, biomass, mobility, local ecosystems, telecommunications) • Construction of monitoring and early warning systems; Measures to identify exposed areas, assist vulnerable areas and households, and diversify livelihoods • Economic diversification		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Increased risk of heat-related mortality (*high confidence*) [24.4]	• Heat health warning systems • Urban planning to reduce heat islands; Improvement of the built environment; Development of sustainable cities • New work practices to avoid heat stress among outdoor workers		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Increased risk of drought-related water and food shortage causing malnutrition (*high confidence*) [24.4]	• Disaster preparedness including early-warning systems and local coping strategies • Adaptive/integrated water resource management • Water infrastructure and reservoir development • Diversification of water sources including water re-use • More efficient use of water (e.g., improved agricultural practices, irrigation management, and resilient agriculture)		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high

southwest and far southeast mainland Australia (*high confidence*) and for some rivers in New Zealand (*medium confidence*). Rising sea levels and increasing heavy rainfall are projected to increase erosion and inundation, with consequent damages to many low-lying ecosystems, infrastructure, and housing (*high confidence*); increasing heat waves will increase risks to human health; rainfall changes and rising temperatures will shift agricultural production zones; and many native species will suffer from range contractions and some may face local or even global extinction. Uncertainty in projected rainfall changes remains large for many parts of Australia and New Zealand, which creates significant challenges for adaptation. Some sectors in some locations have the potential to benefit from projected changes in climate and increasing atmospheric CO_2, for example due to reduced energy demand for winter heating in New Zealand and southern parts of Australia, and due to forest growth in cooler regions except where soil nutrients or rainfall are limiting. Indigenous peoples in both Australia and New Zealand have higher than average exposure to climate change due to a heavy reliance on climate-sensitive primary industries and strong social connections to the natural environment, and face additional constraints to adaptation (*medium confidence*). [25.2, 25.3, 25.5 to 25.8, Boxes 25-1, 25-2, 25-5, and 25-8]

***North America*. Many climate-related hazards that carry risk, particularly related to severe heat, heavy precipitation, and declining snowpack, will increase in frequency and/or severity in North America in the next decades (*very high confidence*).** Climate

Table TS.5 (continued)

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Australasia

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Significant change in community composition and structure of coral reef systems in Australia (*high confidence*) [25.6, 30.5, Boxes CC-CR and CC-OA]	• Ability of corals to adapt naturally appears limited and insufficient to offset the detrimental effects of rising temperatures and acidification. • Other options are mostly limited to reducing other stresses (water quality, tourism, fishing) and early warning systems; direct interventions such as assisted colonization and shading have been proposed but remain untested at scale.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Increased frequency and intensity of flood damage to infrastructure and settlements in Australia and New Zealand (*high confidence*) [Table 25-1, Boxes 25-8 and 25-9]	• Significant adaptation deficit in some regions to current flood risk. • Effective adaptation includes land-use controls and relocation as well as protection and accommodation of increased risk to ensure flexibility.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Increasing risks to coastal infrastructure and low-lying ecosystems in Australia and New Zealand, with widespread damage towards the upper end of projected sea-level-rise ranges (*high confidence*) [25.6, 25.10, Box 25-1]	• Adaptation deficit in some locations to current coastal erosion and flood risk. Successive building and protection cycles constrain flexible responses. • Effective adaptation includes land-use controls and ultimately relocation as well as protection and accommodation.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high

North America

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Wildfire-induced loss of ecosystem integrity, property loss, human morbidity, and mortality as a result of increased drying trend and temperature trend (*high confidence*) [26.4, 26.8, Box 26-2]	• Some ecosystems are more fire-adapted than others. Forest managers and municipal planners are increasingly incorporating fire protection measures (e.g., prescribed burning, introduction of resilient vegetation). Institutional capacity to support ecosystem adaptation is limited. • Adaptation of human settlements is constrained by rapid private property development in high-risk areas and by limited household-level adaptive capacity. • Agroforestry can be an effective strategy for reduction of slash and burn practices in Mexico.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Heat-related human mortality (*high confidence*) [26.6, 26.8]	• Residential air conditioning (A/C) can effectively reduce risk. However, availability and usage of A/C is highly variable and is subject to complete loss during power failures. Vulnerable populations include athletes and outdoor workers for whom A/C is not available. • Community- and household-scale adaptations have the potential to reduce exposure to heat extremes via family support, early heat warning systems, cooling centers, greening, and high-albedo surfaces.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Urban floods in riverine and coastal areas, inducing property and infrastructure damage; supply chain, ecosystem, and social system disruption; public health impacts; and water quality impairment, due to sea level rise, extreme precipitation, and cyclones (*high confidence*) [26.2 to 26.4, 26.8]	• Implementing management of urban drainage is expensive and disruptive to urban areas. • Low-regret strategies with co-benefits include less impervious surfaces leading to more groundwater recharge, green infrastructure, and rooftop gardens. • Sea level rise increases water elevations in coastal outfalls, which impedes drainage. In many cases, older rainfall design standards are being used that need to be updated to reflect current climate conditions. • Conservation of wetlands, including mangroves, and land-use planning strategies can reduce the intensity of flood events.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high

change will amplify risks to water resources already affected by non-climatic stressors, with potential impacts associated with decreased snowpack, decreased water quality, urban flooding, and decreased water supplies for urban areas and irrigation (*high confidence*). More adaptation options are available to address water supply deficits than flooding and water quality concerns (*medium confidence*). Ecosystems are under increasing stress from rising temperatures, CO_2 concentrations, and sea levels, with particular vulnerability to climate extremes (*very high confidence*). In many cases, climate stresses exacerbate other anthropogenic influences on ecosystems, including land use changes, non-native species, and pollution. Projected increases in temperature, reductions in precipitation in some regions, and increased frequency of extreme events would result in net productivity declines in major North American crops by the end of the 21st century without adaptation, although some regions, particularly in the north, may benefit. Adaptation, often with mitigation co-benefits, could offset projected negative yield impacts for many crops at 2°C global mean temperature increase above preindustrial levels, with reduced effectiveness of adaptation at 4°C (*high confidence*). Although larger urban centers would have higher adaptive capacities, high population density, inadequate infrastructures, lack of institutional capacity, and degraded natural environments increase future climate risks from heat waves, droughts, storms, and sea level rise (*medium evidence*, *high agreement*). Future risks from climate extremes can be reduced, for example through targeted and sustainable air conditioning, more effective warning and response systems, enhanced pollution controls, urban

Table TS.5 (continued)

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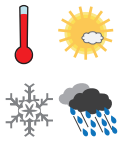
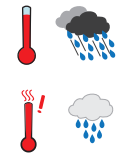
Central and South America

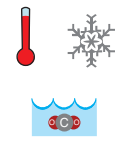


Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Water availability in semi-arid and glacier-melt-dependent regions and Central America; flooding and landslides in urban and rural areas due to extreme precipitation (*high confidence*) [27.3]	• Integrated water resource management • Urban and rural flood management (including infrastructure), early warning systems, better weather and runoff forecasts, and infectious disease control		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high
Decreased food production and food quality (*medium confidence*) [27.3]	• Development of new crop varieties more adapted to climate change (temperature and drought) • Offsetting of human and animal health impacts of reduced food quality • Offsetting of economic impacts of land-use change • Strengthening traditional indigenous knowledge systems and practices		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high
Spread of vector-borne diseases in altitude and latitude (*high confidence*) [27.3]	• Development of early warning systems for disease control and mitigation based on climatic and other relevant inputs. Many factors augment vulnerability. • Establishing programs to extend basic public health services		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high not available not available

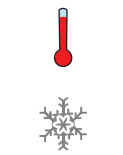


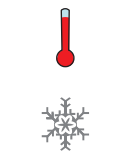


Polar Regions



Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Risks for freshwater and terrestrial ecosystems (*high confidence*) and marine ecosystems (*medium confidence*), due to changes in ice, snow cover, permafrost, and freshwater/ocean conditions, affecting species´ habitat quality, ranges, phenology, and productivity, as well as dependent economies [28.2 to 28.4]	• Improved understanding through scientific and indigenous knowledge, producing more effective solutions and/or technological innovations • Enhanced monitoring, regulation, and warning systems that achieve safe and sustainable use of ecosystem resources • Hunting or fishing for different species, if possible, and diversifying income sources		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high
Risks for the health and well-being of Arctic residents, resulting from injuries and illness from the changing physical environment, food insecurity, lack of reliable and safe drinking water, and damage to infrastructure, including infrastructure in permafrost regions (*high confidence*) [28.2 to 28.4]	• Co-production of more robust solutions that combine science and technology with indigenous knowledge • Enhanced observation, monitoring, and warning systems • Improved communications, education, and training • Shifting resource bases, land use, and/or settlement areas		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high
Unprecedented challenges for northern communities due to complex inter-linkages between climate-related hazards and societal factors, particularly if rate of change is faster than social systems can adapt (*high confidence*) [28.2 to 28.4]	• Co-production of more robust solutions that combine science and technology with indigenous knowledge • Enhanced observation, monitoring, and warning systems • Improved communications, education, and training • Adaptive co-management responses developed through the settlement of land claims		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high





Small Islands



Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Loss of livelihoods, coastal settlements, infrastructure, ecosystem services, and economic stability (*high confidence*) [29.6, 29.8, Figure 29-4]	• Significant potential exists for adaptation in islands, but additional external resources and technologies will enhance response. • Maintenance and enhancement of ecosystem functions and services and of water and food security • Efficacy of traditional community coping strategies is expected to be substantially reduced in the future.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high
The interaction of rising global mean sea level in the 21st century with high-water-level events will threaten low-lying coastal areas (*high confidence*) [29.4, Table 29-1; WGI AR5 13.5, Table 13.5]	• High ratio of coastal area to land mass will make adaptation a significant financial and resource challenge for islands. • Adaptation options include maintenance and restoration of coastal landforms and ecosystems, improved management of soils and freshwater resources, and appropriate building codes and settlement patterns.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high



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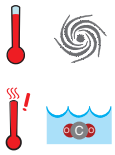
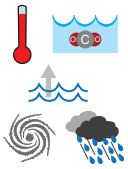
Table TS.5 (continued)

The Ocean				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Distributional shift in fish and invertebrate species, and decrease in fisheries catch potential at low latitudes, e.g., in equatorial upwelling and coastal boundary systems and sub-tropical gyres (*high confidence*) [6.3, 30.5, 30.6, Tables 6-6 and 30-3, Box CC-MB]	• Evolutionary adaptation potential of fish and invertebrate species to warming is limited as indicated by their changes in distribution to maintain temperatures. • Human adaptation options: Large-scale translocation of industrial fishing activities following the regional decreases (low latitude) vs. possibly transient increases (high latitude) in catch potential; Flexible management that can react to variability and change; Improvement of fish resilience to thermal stress by reducing other stressors such as pollution and eutrophication; Expansion of sustainable aquaculture and the development of alternative livelihoods in some regions.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high
Reduced biodiversity, fisheries abundance, and coastal protection by coral reefs due to heat-induced mass coral bleaching and mortality increases, exacerbated by ocean acidification, e.g., in coastal boundary systems and sub-tropical gyres (*high confidence*) [5.4, 6.4, 30.3, 30.5, 30.6, Tables 6-6 and 30-3, Box CC-CR]	• Evidence of rapid evolution by corals is very limited. Some corals may migrate to higher latitudes, but entire reef systems are not expected to be able to track the high rates of temperature shifts. • Human adaptation options are limited to reducing other stresses, mainly by enhancing water quality, and limiting pressures from tourism and fishing. These options will delay human impacts of climate change by a few decades, but their efficacy will be severely reduced as thermal stress increases.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high
Coastal inundation and habitat loss due to sea level rise, extreme events, changes in precipitation, and reduced ecological resilience, e.g., in coastal boundary systems and sub-tropical gyres (*medium* to *high confidence*) [5.5, 30.5, 30.6, Tables 6-6 and 30-3, Box CC-CR]	• Human adaptation options are limited to reducing other stresses, mainly by reducing pollution and limiting pressures from tourism, fishing, physical destruction, and unsustainable aquaculture. • Reducing deforestation and increasing reforestation of river catchments and coastal areas to retain sediments and nutrients • Increased mangrove, coral reef, and seagrass protection, and restoration to protect numerous ecosystem goods and services such as coastal protection, tourist value, and fish habitat		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low / Medium / Very high

TS

planning strategies, and resilient health infrastructure (*high confidence*). [26.3 to 26.6, 26.8]

***Central and South America*. Despite improvements, high and persistent levels of poverty in most countries result in high vulnerability to climate variability and change (*high confidence*).** Climate change impacts on agricultural productivity are expected to exhibit large spatial variability, for example with sustained or increased productivity through mid-century in southeast South America and decreases in productivity in the near term (by 2030) in Central America, threatening food security of the poorest populations (*medium confidence*). Reduced precipitation and increased evapotranspiration in semi-arid regions will increase risks from water-supply shortages, affecting cities, hydropower generation, and agriculture (*high confidence*). Ongoing adaptation strategies include reduced mismatch between water supply and demand, and water-management and coordination reforms (*medium confidence*). Conversion of natural ecosystems, a driver of anthropogenic climate change, is the main cause of biodiversity and ecosystem loss (*high confidence*). Climate change is expected to increase rates of species extinction (*medium confidence*). In coastal and marine systems, sea level rise and human stressors increase risks for fish stocks, corals, mangroves, recreation and tourism, and control of diseases (*high confidence*). Climate change will exacerbate future health risks given regional population growth rates and vulnerabilities due to pollution, food insecurity in poor regions, and existing health, water, sanitation, and waste collection systems (*medium confidence*). [27.2, 27.3]

***Polar Regions*. Climate change and often-interconnected non-climate-related drivers, including environmental changes, demography, culture, and economic development, interact in the Arctic to determine physical, biological, and socioeconomic risks, with rates of change that may be faster than social systems can adapt (*high confidence*).** Thawing permafrost and changing precipitation patterns have the potential to affect infrastructure and related services, with particular risks for residential buildings, for example in Arctic cities and small rural settlements. Climate change will especially impact Arctic communities that have narrowly based economies limiting adaptive choices. Increased Arctic navigability and expanded land- and freshwater-based transportation networks will increase economic opportunities. Impacts on the informal, subsistence-based economy will include changing sea ice conditions that increase the difficulty of hunting marine mammals. Polar bears have been and will be affected by loss of annual ice over continental shelves, decreased ice duration, and decreased ice thickness. Already, accelerated rates of change in permafrost thaw, loss of coastal sea ice, sea level rise, and increased intensity of weather extremes are forcing relocation of some indigenous communities in Alaska (*high confidence*). In the Arctic and Antarctic, some marine species will shift their ranges in response to changing ocean and sea ice conditions (*medium confidence*). Climate change will increase the vulnerability of terrestrial ecosystems to invasions by non-indigenous species (*high confidence*). [6.3, 6.5, 28.2 to 28.4]

***Small Islands*. Small islands have high vulnerability to climatic and non-climatic stressors (*high confidence*).** Diverse physical and human attributes and their sensitivity to climate-related drivers lead to variable climate change risk profiles and adaptation from one island region to another and among countries in the same region. Risks can originate from transboundary interactions, for example associated with existing and future invasive species and human health challenges. Sea level rise poses one of the most widely recognized climate change threats to low-lying coastal areas on islands and atolls. Projected sea level rise at the end of the 21st century, superimposed on extreme-sea-level events, presents severe coastal flooding and erosion risks for low-lying coastal areas and atoll islands. Wave over-wash will degrade groundwater resources. Coral reef ecosystem degradation associated with increasing sea surface temperature and ocean acidification will

Table TS.6 | Observed and projected future changes in some types of temperature and precipitation extremes over 26 sub-continental regions as defined in the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX). Confidence levels are indicated by symbol color. Likelihood terms are given only for *high* or *very high confidence* statements. Observed trends in temperature and precipitation extremes, including dryness and drought, are generally calculated from 1950, using 1961–1990 as the reference period, unless otherwise indicated. Future changes are derived from global and regional climate model projections for 2071–2100 compared with 1961–1990 or for 2080–2100 compared with 1980–2000. Table entries are summaries of information in SREX Tables 3-2 and 3-3 supplemented with or superseded by material from WGI AR5 2.6, 14.8, and Table 2.13 and WGII AR5 Table 25-1. The source(s) of information for each entry are indicated by superscripts: (a) SREX Table 3-2; (b) SREX Table 3-3; (c) WGI AR5 2.6 and Table 2.13; (d) WGI AR5 14.8; (e) WGII AR5 Table 25-1. [Tables 21-7 and SM21-2, Figure 21-4]

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected
West North America WNA, 3	*Very likely* large increases in hot days (large decreases in cool days)[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends. General increase, decrease in some areas[a]	Increase in 20-year return value of annual maximum daily precipitation and other metrics over northern part of the region (Canada)[b] Less confidence in southern part of the region, due to inconsistent signal in these other metrics[b]	No change or overall slight decrease in dryness[a]	Inconsistent signal[b]
Central North America CNA, 4	Spatially varying trends: small increases in hot days in the north, decreases in the south[a]	*Very likely* increase in hot days (decrease in cool days)[b]	*Very likely* increase since 1950[a]	Increase in 20-year return value of annual maximum daily precipitation[b] Inconsistent signal in other heavy precipitation days metrics[b]	*Likely* decrease[a, c]	Increase in consecutive dry days and soil moisture in southern part of central North America[b] Inconsistent signal in the rest of the region[b]
East North America ENA, 5	Spatially varying trends. Overall increases in hot days (decreases in cool days), opposite or insignificant signal in a few areas[a]	*Very likely* increase in hot days (decrease in cool days)[b]	*Very likely* increase since 1950[a]	Increase in 20-year return value of annual maximum daily precipitation. Additional metrics support an increase in heavy precipitation over northern part of the region.[b] No signal or inconsistent signal in these other metrics in the southern part of the region[b]	Slight decrease in dryness since 1950[a]	Inconsistent signal in consecutive dry days, some consistent decrease in soil moisture[b]
Alaska/ Northwest Canada ALA, 1	*Very likely* large increases in hot days (decreases in cool days)[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Slight tendency for increase[a] No significant trend in southern Alaska[a]	*Likely* increase in heavy precipitation[b]	Inconsistent trends[a] Increase in dryness in part of the region[a]	Inconsistent signal[b]
East Canada, Greenland, Iceland CGI, 2	*Likely* increases in hot days (decreases in cool days) in some areas, decrease in hot days (increase in cool days) in others[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Increase in a few areas[a]	*Likely* increase in heavy precipitation[b]	Insufficent evidence[a]	Inconsistent signal[b]
Northern Europe NEU, 11	Increase in hot days (decrease in cool days), but generally not significant at the local scale[a]	*Very likely* increase in hot days (decrease in cool days) [but smaller trends than in central and southern Europe][b]	Increase in winter in some areas, but often insignificant or inconsistent trends at sub-regional scale, particularly in summer[a]	*Likely* increase in 20-year return value of annual maximum daily precipitation. *Very likely* increases in heavy preciptation intensity and frequency in winter in the north[b]	Spatially varying trends. Overall only slight or no increase in dryness, slight decrease in dryness in part of the region[a]	No major changes in dryness[b]

Symbols

Increasing trend or signal | Decreasing trend or signal | Both increasing and decreasing trend or signal | Inconsistent trend or signal or insufficient evidence | No change or only slight change

Level of confidence in findings

Low confidence | *Medium confidence* | *High confidence*

Continued next page →

Table TS.6 (continued)

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected
Central Europe CEU, 12	*Likely* overall increase in hot days (decrease in cool days) in most regions. *Very likely* increase in hot days (*likely* decrease in cool days) in west-central Europe[a] Lower confidence in trends in east-central Europe (due to lack of literature, partial lack of access to observations, overall weaker signals, and change point in trends)[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Increase in part of the region, in particular central western Europe and European Russia, especially in winter.[a] Insignificant or inconsistent trends elsewhere, in particular in summer[a]	*Likely* increase in 20-year return value of annual maximum daily precipitation. Additional metrics support an increase in heavy precipitation in large part of the region in winter.[b] Less confidence in summer, due to inconsistent evidence[b]	Spatially varying trends. Increase in dryness in part of the region but some regional variation in dryness trends and dependence of trends on studies considered (index, time period)[a]	Increase in dryness in central Europe and increase in short-term droughts[b]
Southern Europe and Mediterranean MED, 13	*Likely* increase in hot days (decrease in cool days) in most of the region. Some regional and temporal variations in the significance of the trends. *Likely* strongest and most significant trends in Iberian peninsula and southern France[a] Smaller or less significant trends in southeastern Europe and Italy due to change point in trends, strongest increase in hot days since 1976[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Inconsistent trends across the region and across studies[a]	Inconsistent changes and/or regional variations[b]	Overall increase in dryness, *likely* increase in the Mediterranean[a, c]	Increase in dryness. Consistent increase in area of drought[b, d]
West Africa WAF, 15	Significant increase in temperature of hottest day and coolest day in some parts[a] Insufficient evidence in other parts[a]	*Likely* increase in hot days (decrease in cool days)[b]	Rainfall intensity increased[a]	Slight or no change in heavy precipitation indicators in most areas[b] Low model agreement in northern areas[b]	*Likely* increase but 1970s Sahel drought dominates the trend; greater inter-annual variation in recent years[a, c]	Inconsistent signal[b]
East Africa EAF, 16	Lack of evidence due to lack of literature and spatially non-uniform trends[a] Increases in hot days in southern tip (decreases in cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Insufficient evidence[a]	*Likely* increase in heavy precipitation[b]	Spatially varying trends in dryness[a]	Decreasing dryness in large areas[b]
Southern Africa SAF, 17	*Likely* increase in hot days (decrease in cool days)[a, c]	*Likely* increase in hot days (decrease in cool days)[b]	Increases in more regions than decreases but spatially varying trends[a,c]	Lack of agreement in signal for region as a whole[b] Some evidence of increase in heavy precipitation in southeast regions[b]	General increase in dryness[a]	Increase in dryness, except eastern part[b, d] Consistent increase in area of drought[b]
Sahara SAH, 14	Lack of literature[a]	*Likely* increase in hot days (decrease in cool days)[b]	Insufficient evidence[a]	*Low agreement*[b]	Limited data, spatial variation of the trends[a]	Inconsistent signal of change[b]
Central America and Mexico CAM, 6	Increases in the number of hot days, decreases in the number of cool days[a]	*Likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends. Increase in many areas, decrease in a few others[a]	Inconsistent trends[b]	Varying and inconsistent trends[a]	Increase in dryness in Central America and Mexico, with less confidence in trend in extreme south of region[b]

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Table TS.6 (continued)

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected
Amazon AMZ, 7	Insufficient evidence to identify trends[a]	Hot days *likely* to increase (cool days *likely* to decrease)[b]	Increase in many areas, decrease in a few[a]	Tendency for increases in heavy precipitation events in some metrics[b]	Decrease in dryness for much of the region. Some opposite trends and inconsistencies[a]	Inconsistent signals[b]
Northeastern Brazil NEB, 8	Increases in the number of hot days[a]	Hot days *likely* to increase (cool days *likely* to decrease)[b]	Increase in many areas, decrease in a few[a]	Slight or no change[b]	Varying and inconsistent trends[a]	Increase in dryness[b]
Southeastern South America SSA, 10	Spatially varying trends (increases in hot days in some areas, decreases in others)[a]	Hot days *likely* to increase (cool days *likely* to decrease)[b]	Increase in northern areas[a] Insufficient evidence in southern areas[a]	Increases in northern areas[b] Insufficient evidence in southern areas[b]	Varying and inconsistent trends[a]	Inconsistent signals[b]
West Coast South America WSA, 9	Spatially varying trends (increases in hot days in some areas, decreases in others)[a]	Hot days *likely* to increase (cool days *likely* to decrease)[b]	Decrease in many areas, increase in a few areas[a]	Increases in tropics[b] *Low confidence* in extratropics[b]	Varying and inconsistent trends[a]	Decrease in consecutive dry days in the tropics, and increase in the extratropics[b] Increase in consecutive dry days and soil moisture in southwest South America[b]
North Asia NAS, 18	*Likely* increases in hot days (decreases in cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Increase in some regions, but spatial variation[a]	*Likely* increase in heavy precipitation for most regions[b]	Spatially varying trends[a]	Inconsistent signal of change[b]
Central Asia CAS, 20	*Likely* increases in hot days (decreases in cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends[a]	Inconsistent signal in models[b]	Spatially varying trends[a]	Inconsistent signal of change[b]
East Asia EAS, 22	*Likely* increases in hot days (decreases in cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends[a]	Increases in heavy precipitation across the region[b]	Tendency for increased dryness[a]	Inconsistent signal of change[b]
Southeast Asia SEA, 24	Increases in hot days (decreases in cool days) for northern areas[a] Insufficient evidence for Malay Archipelago[a]	*Likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends, partial lack of evidence[a]	Increases in most metrics over most (especially non-continental) regions. One metric shows inconsistent signals of change.[b]	Spatially varying trends[a]	Inconsistent signal of change[b]
South Asia SAS, 23	Increase in hot days (decrease in cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Mixed signal in India[a]	More frequent and intense heavy precipitation days over parts of South Asia. Either no change or some consistent increases in other metrics[b]	Inconsistent signal for different studies and indices[a]	Inconsistent signal of change[b]
West Asia WAS, 19	*Very likely* increase in hot days (decrease in cool days *more likely than not*)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Decrease in heavy precipitation events[a]	Inconsistent signal of change[b]	Lack of studies, mixed results[a]	Inconsistent signal of change[b]
Tibetan Plateau TIB, 21	*Likely* increase in hot days (decrease in cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Insufficient evidence[a]	Increase in heavy precipitation[b]	Insufficient evidence. Tendency to decreased dryness[a]	Inconsistent signal of change[b]
North Australia NAU, 25	*Likely* increase in hot days (decrease in cool days). Weaker trends in northwest[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends, which mostly reflect changes in mean rainfall[e]	Increase in most regions in the intensity of extreme (i.e., current 20-year return period) heavy rainfall events[e]	No significant change in drought occurrence over Australia (defined using rainfall anomalies)[e]	Inconsistent signal[b]

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Table TS.6 (continued)

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected
South Australia/ New Zealand SAU, 26	*Very likely* increase in hot days (decrease in cool days)[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends in southern Australia, which mostly reflect changes in mean rainfall[e] Spatially varying trends in New Zealand, which mostly reflect changes in mean rainfall[e]	Increase in most regions in the intensity of extreme (i.e., current 20-year return period) heavy rainfall events[e]	No significant change in drought occurrence over Australia (defined using rainfall anomalies)[e] No trend in drought occurrence over New Zealand (defined using a soil–water balance model) since 1972[e]	Increase in drought frequency in southern Australia, and in many regions of New Zealand[e]

negatively impact island communities and livelihoods, given the dependence of island communities on coral reef ecosystems for coastal protection, subsistence fisheries, and tourism. [29.3 to 29.5, 29.9, 30.5, Figure 29-1, Table 29-3, Box CC-CR]

***The Ocean*. Warming will increase risks to ocean ecosystems (*high confidence*).** Coral reefs within coastal boundary systems, semi-enclosed seas, and subtropical gyres are rapidly declining as a result of local non-climatic stressors (i.e., coastal pollution, overexploitation) and climate change. Projected increases in mass coral bleaching and mortality will alter or eliminate ecosystems, increasing risks to coastal livelihoods and food security (*medium* to *high confidence*). An analysis of the CMIP5 ensemble projects loss of coral reefs from most sites globally to be *very likely* by 2050 under mid to high rates of ocean warming. Reducing non-climatic stressors represents an opportunity to strengthen ecological resilience. The highly productive high-latitude spring bloom systems in the northeastern Atlantic are responding to warming (*medium evidence*, *high agreement*), with the greatest changes being observed since the late 1970s in the phenology, distribution, and abundance of plankton assemblages, and the reorganization of fish assemblages, with a range of consequences for fisheries (*high confidence*). Projected warming increases the likelihood of greater thermal stratification in some regions, which can lead to reduced O_2 ventilation and encourage the formation of hypoxic zones, especially in the Baltic and Black Seas (*medium confidence*). Changing surface winds and waves, sea level, and storm intensity will increase the vulnerability of ocean-based industries such as shipping, energy, and mineral extraction. New opportunities as well as international issues over access to resources and vulnerability may accompany warming waters particularly at high latitudes. [5.3, 5.4, 6.4, 28.2, 28.3, 30.3, 30.5, 30.6, Table 30-1, Figures 30-4 and 30-10, Boxes 6-1, CC-CR, and CC-MB]

Understanding of extreme events and their interactions with climate change is particularly important for managing risks in a regional context. Table TS.6 provides a summary of observed and projected trends in some types of temperature and precipitation extremes.

C: MANAGING FUTURE RISKS AND BUILDING RESILIENCE

Managing the risks of climate change involves adaptation and mitigation decisions with implications for future generations, economies, and environments. Figure TS.12 provides an overview of responses for addressing risk related to climate change.

Starting with principles for effective adaptation, this section evaluates the ways that interlinked human and natural systems can build resilience through adaptation, mitigation, and sustainable development. It describes understanding of climate-resilient pathways, of incremental versus transformational changes, and of limits to adaptation, and it considers co-benefits, synergies, and trade-offs among mitigation, adaptation, and development.

C-1. Principles for Effective Adaptation

The report assesses a wide variety of approaches for reducing and managing risks and building resilience. Strategies and approaches to climate change adaptation include efforts to decrease vulnerability or exposure and/or increase resilience or adaptive capacity. Mitigation is assessed in the WGIII AR5. Specific examples of responses to climate change are presented in Table TS.7.

Adaptation is place- and context-specific, with no single approach for reducing risks appropriate across all settings (*high confidence*). Effective risk reduction and adaptation strategies consider the dynamics of vulnerability and exposure and their linkages with socioeconomic processes, sustainable development, and climate change. [2.1, 8.3, 8.4, 13.1, 13.3, 13.4, 15.2, 15.3, 15.5, 16.2, 16.3, 16.5, 17.2, 17.4, 19.6, 21.3, 22.4, 26.8, 26.9, 29.6, 29.8]

Adaptation planning and implementation can be enhanced through complementary actions across levels, from individuals to governments (*high confidence*). National governments can coordinate adaptation efforts of local and subnational governments, for example by protecting vulnerable groups, by supporting economic diversification, and by providing information, policy and legal frameworks, and financial support (*robust evidence*, *high agreement*). Local government and the private sector are increasingly recognized as critical to progress in adaptation, given their roles in scaling up adaptation of communities, households, and civil society and in managing risk information and financing (*medium evidence*, *high agreement*). [2.1 to 2.4, 3.6, 5.5, 8.3, 8.4, 9.3, 9.4, 14.2, 15.2, 15.3, 15.5, 16.2 to 16.5, 17.2, 17.3, 22.4, 24.4, 25.4, 26.8, 26.9, 30.7, Tables 21-1, 21-5, and 21-6, Box 16-2]

A first step towards adaptation to future climate change is reducing vulnerability and exposure to present climate variability (*high confidence*). Strategies include actions with co-benefits for other objectives. Available strategies and actions can increase resilience across a range of possible future climates while helping to improve human health, livelihoods, social and economic well-being, and environmental quality. Examples of adaptation strategies that also strengthen livelihoods, enhance development, and reduce poverty include improved social protection, improved water and land governance, enhanced water storage and services, greater involvement in planning, and elevated attention to urban and peri-urban areas heavily affected by migration of poor people. See Table TS.7. [3.6, 8.3, 9.4, 14.3, 15.2, 15.3, 17.2, 20.4, 20.6, 22.4, 24.4, 24.5, 25.4, 25.10, 27.3 to 27.5, 29.6, Boxes 25-2 and 25-6]

Adaptation planning and implementation at all levels of governance are contingent on societal values, objectives, and risk perceptions (*high confidence*). Recognition of diverse interests, circumstances, social-cultural contexts, and expectations can

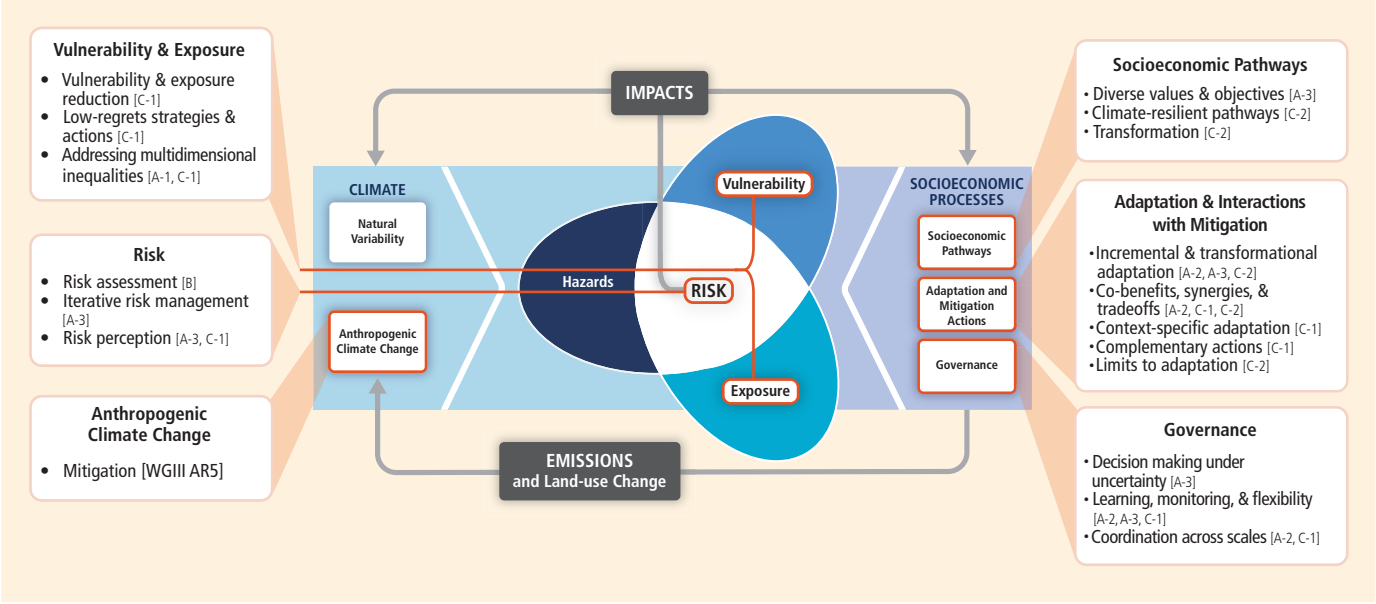


Figure TS.12 | The solution space. Core concepts of the WGII AR5, illustrating overlapping entry points and approaches, as well as key considerations, in managing risks related to climate change, as assessed in the report and presented throughout this summary. Bracketed references indicate sections of the summary with corresponding assessment findings.

Table TS.7 | Approaches for managing the risks of climate change. These approaches should be considered overlapping rather than discrete, and they are often pursued simultaneously. Mitigation is considered essential for managing the risks of climate change. It is not addressed in this table as mitigation is the focus of WGIII AR5. Examples are presented in no specific order and can be relevant to more than one category. [14.2, 14.3, Table 14-1]

Overlapping Approaches	Category	Examples	Chapter Reference(s)
Vulnerability & Exposure Reduction through development, planning, & practices including many low-regrets measures	Human development	Improved access to education, nutrition, health facilities, energy, safe housing & settlement structures, & social support structures; Reduced gender inequality & marginalization in other forms.	8.3, 9.3, 13.1 to 13.3, 14.2, 14.3, 22.4
	Poverty alleviation	Improved access to & control of local resources; Land tenure; Disaster risk reduction; Social safety nets & social protection; Insurance schemes.	8.3, 8.4, 9.3, 13.1 to 13.3
	Livelihood security	Income, asset, & livelihood diversification; Improved infrastructure; Access to technology & decision-making fora; Increased decision-making power; Changed cropping, livestock, & aquaculture practices; Reliance on social networks.	7.5, 9.4, 13.1 to 13.3, 22.3, 22.4, 23.4, 26.5, 27.3, 29.6, Table SM24-7
	Disaster risk management	Early warning systems; Hazard & vulnerability mapping; Diversifying water resources; Improved drainage; Flood & cyclone shelters; Building codes & practices; Storm & wastewater management; Transport & road infrastructure improvements.	8.2 to 8.4, 11.7, 14.3, 15.4, 22.4, 24.4, 26.6, 28.4, Table 3-3, Box 25-1
	Ecosystem management	Maintaining wetlands & urban green spaces; Coastal afforestation; Watershed & reservoir management; Reduction of other stressors on ecosystems & of habitat fragmentation; Maintenance of genetic diversity; Manipulation of disturbance regimes; Community-based natural resource management.	4.3, 4.4, 8.3, 22.4, Table 3-3, Boxes 4-3, 8-2, 15-1, 25-8, 25-9, & CC-EA
	Spatial or land-use planning	Provisioning of adequate housing, infrastructure, & services; Managing development in flood prone & other high risk areas; Urban planning & upgrading programs; Land zoning laws; Easements; Protected areas.	4.4, 8.1 to 8.4, 22.4, 23.7, 23.8, 27.3, Box 25-8
Adaptation including incremental & transformational adjustments	Structural/physical	***Engineered & built-environment options***: Sea walls & coastal protection structures; Flood levees; Water storage; Improved drainage; Flood & cyclone shelters; Building codes & practices; Storm & wastewater management; Transport & road infrastructure improvements; Floating houses; Power plant & electricity grid adjustments.	3.5, 3.6, 5.5, 8.2, 8.3, 10.2, 11.7, 23.3, 24.4, 25.7, 26.3, 26.8, Boxes 15-1, 25-1, 25-2, & 25-8
		Technological options: New crop & animal varieties; Indigenous, traditional, & local knowledge, technologies, & methods; Efficient irrigation; Water-saving technologies; Desalinization; Conservation agriculture; Food storage & preservation facilities; Hazard & vulnerability mapping & monitoring; Early warning systems; Building insulation; Mechanical & passive cooling; Technology development, transfer, & diffusion.	7.5, 8.3, 9.4, 10.3, 15.4, 22.4, 24.4, 26.3, 26.5, 27.3, 28.2, 28.4, 29.6, 29.7, Tables 3-3 & 15-1, Boxes 20-5 & 25-2
		Ecosystem-based options: Ecological restoration; Soil conservation; Afforestation & reforestation; Mangrove conservation & replanting; Green infrastructure (e.g., shade trees, green roofs); Controlling overfishing; Fisheries co-management; Assisted species migration & dispersal; Ecological corridors; Seed banks, gene banks, & other *ex situ* conservation; Community-based natural resource management.	4.4, 5.5, 6.4, 8.3, 9.4, 11.7, 15.4, 22.4, 23.6, 23.7, 24.4, 25.6, 27.3, 28.2, 29.7, 30.6, Boxes 15-1, 22-2, 25-9, 26-2, & CC-EA
		Services: Social safety nets & social protection; Food banks & distribution of food surplus; Municipal services including water & sanitation; Vaccination programs; Essential public health services; Enhanced emergency medical services.	3.5, 3.6, 8.3, 9.3, 11.7, 11.9, 22.4, 29.6, Box 13-2
	Institutional	***Economic options***: Financial incentives; Insurance; Catastrophe bonds; Payments for ecosystem services; Pricing water to encourage universal provision and careful use; Microfinance; Disaster contingency funds; Cash transfers; Public-private partnerships.	8.3, 8.4, 9.4, 10.7, 11.7, 13.3, 15.4, 17.5, 22.4, 26.7, 27.6, 29.6, Box 25-7
		Laws & regulations: Land zoning laws; Building standards & practices; Easements; Water regulations & agreements; Laws to support disaster risk reduction; Laws to encourage insurance purchasing; Defined property rights & land tenure security; Protected areas; Fishing quotas; Patent pools & technology transfer.	4.4, 8.3, 9.3, 10.5, 10.7, 15.2, 15.4, 17.5, 22.4, 23.4, 23.7, 24.4, 25.4, 26.3, 27.3, 30.6, Table 25-2, Box CC-CR
		National & government policies & programs: National & regional adaptation plans including mainstreaming; Sub-national & local adaptation plans; Economic diversification; Urban upgrading programs; Municipal water management programs; Disaster planning & preparedness; Integrated water resource management; Integrated coastal zone management; Ecosystem-based management; Community-based adaptation.	2.4, 3.6, 4.4, 5.5, 6.4, 7.5, 8.3, 11.7, 15.2 to 15.5, 22.4, 23.7, 25.4, 25.8, 26.8, 26.9, 27.3, 27.4, 29.6, Tables 9-2 & 17-1, Boxes 25-1, 25-2, & 25-9
	Social	***Educational options***: Awareness raising & integrating into education; Gender equity in education; Extension services; Sharing indigenous, traditional, & local knowledge; Participatory action research & social learning; Knowledge-sharing & learning platforms.	8.3, 8.4, 9.4, 11.7, 12.3, 15.2 to 15.4, 22.4, 25.4, 28.4, 29.6, Tables 15-1 & 25-2
		Informational options: Hazard & vulnerability mapping; Early warning & response systems; Systematic monitoring & remote sensing; Climate services; Use of indigenous climate observations; Participatory scenario development; Integrated assessments.	2.4, 5.5, 8.3, 8.4, 9.4, 11.7, 15.2 to 15.4, 22.4, 23.5, 24.4, 25.8, 26.6, 26.8, 27.3, 28.2, 28.5, 30.6, Table 25-2, Box 26-3
		Behavioral options: Household preparation & evacuation planning; Migration; Soil & water conservation; Storm drain clearance; Livelihood diversification; Changed cropping, livestock, & aquaculture practices; Reliance on social networks.	5.5, 7.5, 9.4, 12.4, 22.3, 22.4, 23.4, 23.7, 25.7, 26.5, 27.3, 29.6, Table SM24-7, Box 25-5
Transformation	Spheres of change	***Practical***: Social & technical innovations, behavioral shifts, or institutional & managerial changes that produce substantial shifts in outcomes.	8.3, 17.3, 20.5, Box 25-5
		Political: Political, social, cultural, & ecological decisions & actions consistent with reducing vulnerability & risk & supporting adaptation, mitigation, & sustainable development.	14.2, 14.3, 20.5, 25.4, 30.7, Table 14-1
		Personal: Individual & collective assumptions, beliefs, values, & worldviews influencing climate-change responses.	14.2, 14.3, 20.5, 25.4, Table 14-1

benefit decision-making processes. Awareness that climate change may exceed the adaptive capacity of some people and ecosystems may have ethical implications for mitigation decisions and investments. Economic analysis of adaptation is moving away from a unique emphasis on efficiency, market solutions, and benefit/cost analysis to include consideration of non-monetary and non-market measures, risks, inequities, behavioral biases, barriers and limits, and ancillary benefits and costs. [2.2 to 2.4, 9.4, 12.3, 13.2, 15.2, 16.2 to 16.4, 16.6, 16.7, 17.2, 17.3, 21.3, 22.4, 24.4, 24.6, 25.4, 25.8, 26.9, 28.2, 28.4, Table 15-1, Boxes 16-1, 16-4, and 25-7]

Indigenous, local, and traditional knowledge systems and practices, including indigenous peoples' holistic view of community and environment, are a major resource for adapting to climate change (*robust evidence*, *high agreement*). Natural resource dependent communities, including indigenous peoples, have a long history of adapting to highly variable and changing social and ecological conditions. But the salience of indigenous, local, and traditional knowledge will be challenged by climate change impacts. Such forms of knowledge have not been used consistently in existing adaptation efforts. Integrating such forms of knowledge with existing practices increases the effectiveness of adaptation. [9.4, 12.3, 15.2, 22.4, 24.4, 24.6, 25.8, 28.2, 28.4, Table 15-1]

Decision support is most effective when it is sensitive to context and the diversity of decision types, decision processes, and constituencies (*robust evidence*, *high agreement*). Organizations bridging science and decision making, including climate services, play an important role in the communication, transfer, and development of climate-related knowledge, including translation, engagement, and knowledge exchange (*medium evidence*, *high agreement*). [2.1 to 2.4, 8.4, 14.4, 16.2, 16.3, 16.5, 21.2, 21.3, 21.5, 22.4, Box 9-4]

Integration of adaptation into planning and decision making can promote synergies with development and disaster risk reduction (*high confidence*). Such mainstreaming embeds climate-sensitive thinking in existing and new institutions and organizations. Adaptation can generate larger benefits when connected with development activities and disaster risk reduction (*medium confidence*). [8.3, 9.3, 14.2, 14.6, 15.3, 15.4, 17.2, 20.2, 20.3, 22.4, 24.5, 29.6, Box CC-UR]

Existing and emerging economic instruments can foster adaptation by providing incentives for anticipating and reducing impacts (*medium confidence*). Instruments include public–private finance partnerships, loans, payments for environmental services, improved resource pricing, charges and subsidies, norms and regulations, and risk sharing and transfer mechanisms. Risk financing mechanisms in the public and private sector, such as insurance and risk pools, can contribute to increasing resilience, but without attention to major design challenges, they can also provide disincentives, cause market failure, and decrease equity. Governments often play key roles as regulators, providers, or insurers of last resort. [10.7, 10.9, 13.3, 17.4, 17.5, Box 25-7]

Constraints can interact to impede adaptation planning and implementation (*high confidence*). Common constraints on implementation arise from the following: limited financial and human resources; limited integration or coordination of governance; uncertainties about projected impacts; different perceptions of risks; competing values; absence of key adaptation leaders and advocates; and limited tools to monitor adaptation effectiveness. Another constraint includes insufficient research, monitoring, and observation and the finance to maintain them. Underestimating the complexity of adaptation as a social process can create unrealistic expectations about achieving intended adaptation outcomes. [3.6, 4.4, 5.5, 8.4, 9.4, 13.2, 13.3, 14.2, 14.5, 15.2, 15.3, 15.5, 16.2, 16.3, 16.5, 17.2, 17.3, 22.4, 23.7, 24.5, 25.4, 25.10, 26.8, 26.9, 30.6, Table 16-3, Boxes 16-1 and 16-3]

Poor planning, overemphasizing short-term outcomes, or failing to sufficiently anticipate consequences can result in maladaptation (*medium evidence*, *high agreement*). Maladaptation can increase the vulnerability or exposure of the target group in the future, or the vulnerability of other people, places, or sectors. Narrow focus on quantifiable costs and benefits can bias decisions against the poor, against ecosystems, and against those in the future whose values can be excluded or are understated. Some near-term responses to increasing risks related to climate change may also limit future choices. For example, enhanced protection of exposed assets can lock in dependence on further protection measures. [5.5, 8.4, 14.6, 15.5, 16.3, 17.2, 17.3, 20.2, 22.4, 24.4, 25.10, 26.8, Table 14-4, Box 25-1]

Limited evidence indicates a gap between global adaptation needs and funds available for adaptation (*medium confidence*). There is a need for a better assessment of global adaptation costs, funding, and investment. Studies estimating the global cost of adaptation are characterized by shortcomings in data, methods, and coverage (*high confidence*). [14.2, 17.4, Tables 17-2 and 17-3]

C-2. Climate-resilient Pathways and Transformation

Climate-resilient pathways are sustainable-development trajectories that combine adaptation and mitigation to reduce climate change and its impacts. They include iterative processes to ensure that effective risk management can be implemented and sustained. See Figure TS.13. [2.5, 20.3, 20.4]

Prospects for climate-resilient pathways for sustainable development are related fundamentally to what the world accomplishes with climate-change mitigation (*high confidence*). Since mitigation reduces the rate as well as the magnitude of warming, it also increases the time available for adaptation to a particular level of climate change, potentially by several decades. Delaying mitigation actions may reduce options for climate-resilient pathways in the future. [1.1, 19.7, 20.2, 20.3, 20.6, Figure 1-5]

Greater rates and magnitude of climate change increase the likelihood of exceeding adaptation limits (*high confidence*). See Box TS.8. Limits to adaptation occur when adaptive actions to avoid intolerable risks for an actor's objectives or for the needs of a system are not possible or are not currently available. Value-based judgments

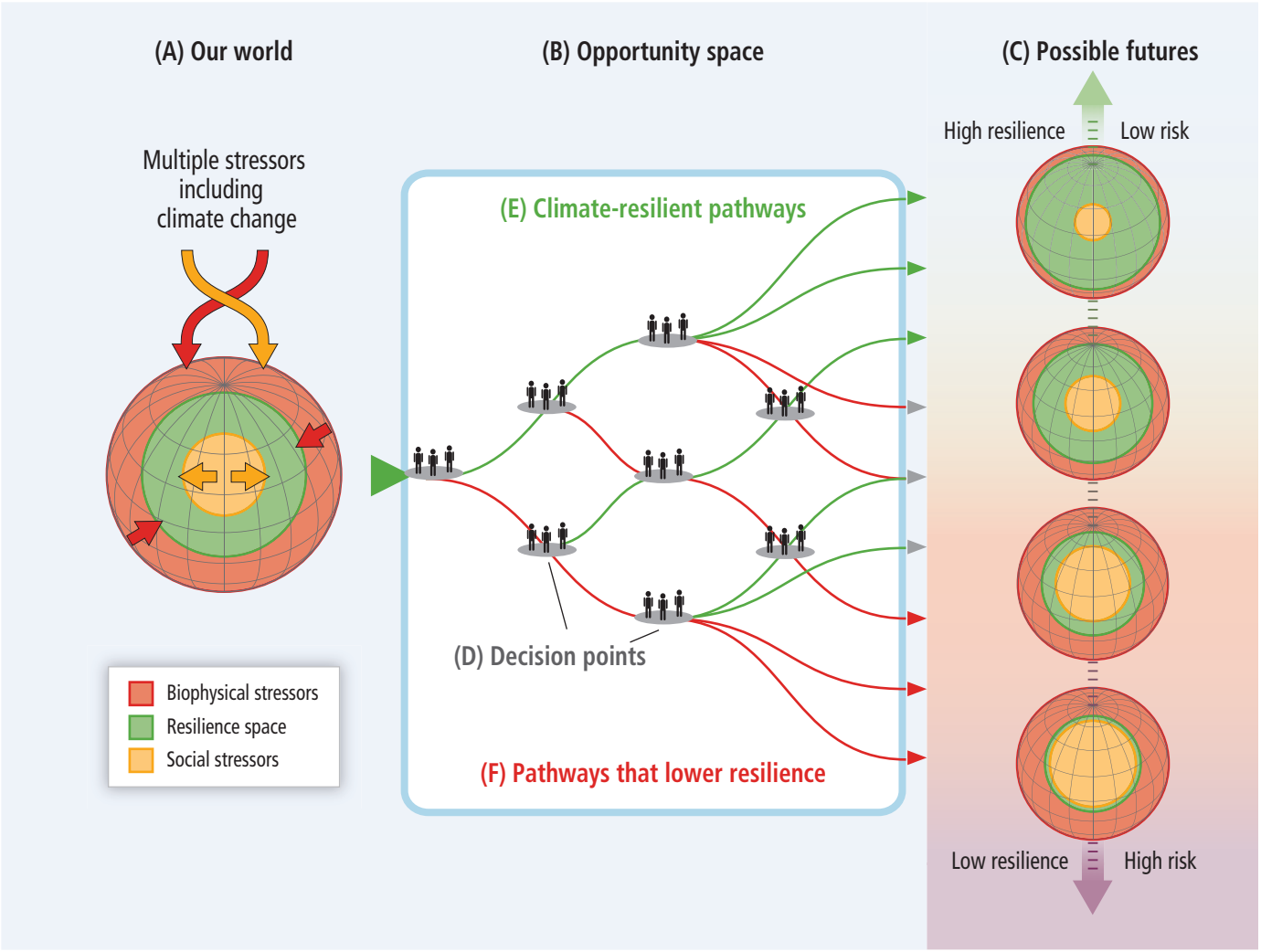


Figure TS.13 | Opportunity space and climate-resilient pathways. (A) Our world [Sections A-1 and B-1] is threatened by multiple stressors that impinge on resilience from many directions, represented here simply as biophysical and social stressors. Stressors include climate change, climate variability, land-use change, degradation of ecosystems, poverty and inequality, and cultural factors. (B) Opportunity space [Sections A-2, A-3, B-2, C-1, and C-2] refers to decision points and pathways that lead to a range of (C) possible futures [Sections C and B-3] with differing levels of resilience and risk. (D) Decision points result in actions or failures-to-act throughout the opportunity space, and together they constitute the process of managing or failing to manage risks related to climate change. (E) Climate-resilient pathways (in green) within the opportunity space lead to a more resilient world through adaptive learning, increasing scientific knowledge, effective adaptation and mitigation measures, and other choices that reduce risks. (F) Pathways that lower resilience (in red) can involve insufficient mitigation, maladaptation, failure to learn and use knowledge, and other actions that lower resilience; and they can be irreversible in terms of possible futures. [Figure 1-5]

of what constitutes an intolerable risk may differ. Limits to adaptation emerge from the interaction among climate change and biophysical and/or socioeconomic constraints. Opportunities to take advantage of positive synergies between adaptation and mitigation may decrease with time, particularly if limits to adaptation are exceeded. In some parts of the world, insufficient responses to emerging impacts are already eroding the basis for sustainable development. [1.1, 11.8, 13.4, 16.2 to 16.7, 17.2, 20.2, 20.3, 20.5, 20.6, 25.10, 26.5, Boxes 16-1, 16-3, and 16-4]

Transformations in economic, social, technological, and political decisions and actions can enable climate-resilient pathways (*high confidence*). Specific examples are presented in Table TS.7. See also Box TS.8. Strategies and actions can be pursued now that will move towards climate-resilient pathways for sustainable development, while at the same time helping to improve livelihoods, social and economic well-being, and responsible environmental management. Transformations in response to climate change may involve, for example, introduction of new technologies or practices, formation of new structures or systems of governance, or shifts in the types or locations of activities. The scale and magnitude of transformational adaptations depend on mitigation and on development processes. Transformational adaptation is an important consideration for decisions involving long life- or lead-times, and it can be a response to adaptation limits. At the national level, transformation is considered most effective when it reflects a country's own visions and approaches to achieving sustainable development in accordance with its national circumstances and priorities. Transformations to sustainability are considered to benefit from iterative learning, deliberative processes, and innovation. Societal debates about many aspects of transformation may place new and increased demands on governance structures. [1.1, 2.1, 2.5, 8.4, 14.1, 14.3, 16.2 to 16.7, 20.5, 22.4, 25.4, 25.10, Figure 1-5, Boxes 16-1 and 16-4]

Examples of Co-benefits, Synergies, and Trade-offs among Adaptation, Mitigation, and Sustainable Development

Significant co-benefits, synergies, and trade-offs exist between mitigation and adaptation and among different adaptation responses; interactions occur both within and across regions (*very high confidence*). Illustrative examples include the following.

- Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, particularly at the intersections among water, energy, land use, and biodiversity, but tools to understand and manage these interactions remain limited (*very high confidence*). See Box TS.9. Widespread transformation of terrestrial ecosystems in order to mitigate climate change, such as carbon sequestration through planting fast-growing tree species into ecosystems where they did not previously occur, or the conversion of previously uncultivated or non-degraded land to bioenergy plantations, can lead to negative impacts on ecosystems and biodiversity (*high confidence*). [3.7, 4.2 to 4.4, 22.6, 24.6, 25.7, 25.9, 27.3, Boxes 25-10 and CC-WE]
- Climate policies such as increasing energy supply from renewable resources, encouraging bioenergy crop cultivation, or facilitating payments under REDD+ will affect some rural areas both positively (e.g., increasing employment opportunities) and negatively (e.g., land use changes, increasing scarcity of natural capital) (*medium confidence*). These secondary impacts, and trade-offs between mitigation and adaptation in rural areas, have implications for governance, including benefits of promoting participation of rural stakeholders. Mitigation policies with social co-benefits expected in their design, such as CDM and REDD+, have had limited or no effect in terms of poverty alleviation and sustainable development

Box TS.8 | Adaptation Limits and Transformation

Adaptation can expand the capacity of natural and human systems to cope with a changing climate. Risk-based decision making can be used to assess potential limits to adaptation. Limits to adaptation occur when adaptive actions to avoid intolerable risks for an actor's objectives or for the needs of a system are not possible or are not currently available. Limits to adaptation are context-specific and closely linked to cultural norms and societal values. Value-based judgments of what constitutes an intolerable risk may differ among actors, but understandings of limits to adaptation can be informed by historical experiences, or by anticipation of impacts, vulnerability, and adaptation associated with different scenarios of climate change. The greater the magnitude or rate of climate change, the greater the likelihood that adaptation will encounter limits. [16.2 to 16.4, 20.5, 20.6, 22.4, 25.4, 25.10, Box 16-2]

Limits to adaptation may be influenced by the subjective values of societal actors, which can affect both the perceived need for adaptation and the perceived appropriateness of specific policies and measures. While limits imply that intolerable risks and the increased potential for losses and damages can no longer be avoided, the dynamics of social and ecological systems mean that there are both "soft" and "hard" limits to adaptation. For "soft" limits, there are opportunities in the future to alter limits and reduce risks, for example, through the emergence of new technologies or changes in laws, institutions, or values. In contrast, "hard" limits are those where there are no reasonable prospects for avoiding intolerable risks. Recent studies on tipping points, key vulnerabilities, and planetary boundaries provide some insights on the behavior of complex systems. [16.2 to 16.7, 25.10]

In cases where the limits to adaptation have been surpassed, losses and damage may increase and the objectives of some actors may no longer be achievable. There may be a need for transformational adaptation to change fundamental attributes of a system in response to actual or expected impacts of climate change. It may involve adaptations at a greater scale or intensity than previously experienced, adaptations that are new to a region or system, or adaptations that transform places or lead to a shift in the types or locations of activities. [16.2 to 16.4, 20.3, 20.5, 22.4, 25.10, Boxes 25-1 and 25-9]

The existence of limits to adaptation suggests transformational change may be a requirement for sustainable development in a changing climate—that is, not only for adapting to the impacts of climate change, but for altering the systems and structures, economic and social relations, and beliefs and behaviors that contribute to climate change and social vulnerability. However, just as there are ethical implications associated with some adaptation options, there are also legitimate concerns about the equity and ethical dimensions of transformation. Societal debates over risks from forced and reactive transformations as opposed to deliberate transitions to sustainability may place new and increased demands on governance structures at multiple levels to reconcile conflicting goals and visions for the future. [1.1, 16.2 to 16.7, 20.5, 25.10]

(*medium confidence*). Mitigation efforts focused on land acquisition for biofuel production show preliminary negative impacts for the poor in many developing countries, and particularly for indigenous people and (women) smallholders. [9.3, 13.3, 22.6]

- Mangrove, seagrass, and salt marsh ecosystems offer important carbon storage and sequestration opportunities (*limited evidence*, *medium agreement*), in addition to ecosystem goods and services such as protection against coastal erosion and storm damage and maintenance of habitats for fisheries species. For ocean-related mitigation and adaptation in the context of anthropogenic ocean warming and acidification, international frameworks offer opportunities to solve problems collectively, for example, managing fisheries across national borders and responding to extreme events. [5.4, 25.6, 30.6, 30.7]

Table TS.8 | Illustrative examples of intra-regional interactions among adaptation, mitigation, and sustainable development.

Green infrastructure and green roofs	
Objectives	Storm water management, adaptation to increasing temperatures, reduced energy use, urban regeneration
Relevant sectors	Infrastructure, energy use, water management
Overview	Benefits of green infrastructure and roofs can include reduction of storm water runoff and the urban heat island effect, improved energy performance of buildings, reduced noise and air pollution, health improvements, better amenity value, increased property values, improved biodiversity, and inward investment. Trade-offs can result between higher urban density to improve energy efficiency and open space for green infrastructure. [8.3.3, 11.7.4, 23.7.4, 24.6, Tables 11-3 and 25-5]
Examples with interactions	**London:** The Green Grid for East London seeks to create interlinked and multi-purpose open spaces to support regeneration of the area. It aims to connect people and places, to absorb and store water, to cool the vicinity, and to provide a diverse mosaic of habitats for wildlife. [8.3.3] **New York:** In preparation for more intense storms, New York is using green infrastructure to capture rainwater before it can flood the combined sewer system, implementing green roofs, and elevating boilers and other equipment above ground. [8.3.3, 26.3.3, 26.8.4] **Singapore:** Singapore has used several anticipatory plans and projects to enhance green infrastructure, including its Streetscape Greenery Master Plan, constructed wetlands or drains, and community gardens. Under its Skyrise Greenery project, Singapore has provided subsidies and handbooks for rooftop and wall greening initiatives. [8.3.3] **Durban:** Ecosystem-based adaptation is part of Durban's climate change adaptation strategy. The approach seeks a more detailed understanding of the ecology of indigenous ecosystems and ways in which biodiversity and ecosystem services can reduce vulnerability of ecosystems and people. Examples include the Community Reforestation Programme, in which communities produce indigenous seedlings used in the planting and managing of restored forest areas. Development of ecosystem-based adaptation in Durban has demonstrated needs for local knowledge and data and the benefits of enhancing existing protected areas, land-use practices, and local initiatives contributing to jobs, business, and skill development. [8.3.3, Box 8-2]
Water management	
Primary objective	Water resource management given multiple stressors in a changing climate
Relevant sectors	Water use, energy production and use, biodiversity, carbon sequestration, biofuel production, food production
Overview	Water management in the context of climate change can encompass ecosystem-based approaches (e.g., watershed management or restoration, flood regulation services, and reduction of erosion or siltation), supply-side approaches (e.g., dams, reservoirs, groundwater pumping and recharge, and water capture), and demand-side approaches (e.g., increased use efficiency through water recycling, infrastructure upgrades, water-sensitive design, or more efficient allocation). Water may require significant amounts of energy for lifting, transport, distribution, and treatment. [3.7.2, 26.3, Tables 9-8 and 25-5, Boxes CC-EA and CC-WE]
Examples with interactions	**New York:** New York has a well-established program to protect and enhance its water supply through watershed protection. The Watershed Protection Program includes city ownership of land that remains undeveloped and coordination with landowners and communities to balance water-quality protection, local economic development, and improved wastewater treatment. The city government indicates it is the most cost-effective choice for New York given the costs and environmental impacts of a filtration plant. [8.3.3, Box 26-3] **Cape Town:** Facing challenges in ensuring future supplies, Cape Town responded by commissioning water management studies, which identified the need to incorporate climate change, as well as population and economic growth, in planning. During the 2005 drought, local authorities increased water tariffs to promote efficient water usage. Additional measures may include water restrictions, reuse of gray water, consumer education, or technological solutions such as low-flow systems or dual flush toilets. [8.3.3] **Capital cities in Australia:** Many Australian capital cities are reducing reliance on catchment runoff and groundwater—water resources most sensitive to climate change and drought—and are diversifying supplies through desalination plants, water reuse including sewage and storm water recycling, and integrated water cycle management that considers climate change impacts. Demand is being reduced through water conservation and water-sensitive urban design and, during severe shortfalls, through implementation of restrictions. The water augmentation program in Melbourne includes a desalination plant. Trade-offs beyond energy intensiveness have been noted, such as damage to sites significant to aboriginal communities and higher water costs that will disproportionately affect poorer households. [14.6.2, Tables 25-6 and 25-7, Box 25-2]
Payment for environmental services and green fiscal policies	
Primary objective	Management incorporating the costs of environmental externalities and the benefits of ecosystem services
Relevant sectors	Biodiversity, ecosystem services
Overview	Payment for environmental services (PES) is a market-based approach that aims to protect natural areas, and associated livelihoods and environmental services, by developing financial incentives for preservation. Mitigation-focused PES schemes are common, and there is emerging evidence of adaptation-focused PES schemes. Successful PES approaches can be difficult to design for services that are hard to define or quantify. [17.5.2, 27.6.2]
Examples with interactions	**Central and South America:** A variety of PES schemes have been implemented in Central and South America. For example, national-level programs have operated in Costa Rica and Guatemala since 1997 and in Ecuador since 2008. Examples to date have shown that PES can finance conservation, ecosystem restoration and reforestation, better land-use practices, mitigation, and more recently adaptation. Uniform payments for beneficiaries can be inefficient if, for example, recipients that promote greater environmental gains receive only the prevailing payment. [17.5.2, 27.3.2, 27.6.2, Table 27-8] **Brazil:** Municipal funding in Brazil tied to ecosystem-management quality is a form of revenue transfer important to funding local adaptation actions. State governments collect a value-added tax redistributed among municipalities, and some states allocate revenues in part based on municipality area set aside for protection. This mechanism has helped improve environmental management and increased creation of protected areas. It benefits relations between protected areas and surrounding inhabitants, as the areas can be perceived as opportunities for revenue generation rather than as obstacles to development. The approach builds on existing institutions and administrative procedures and thus has low transaction costs. [8.4.3, Box 8-4]

Continued next page →

Table TS.8 (continued)

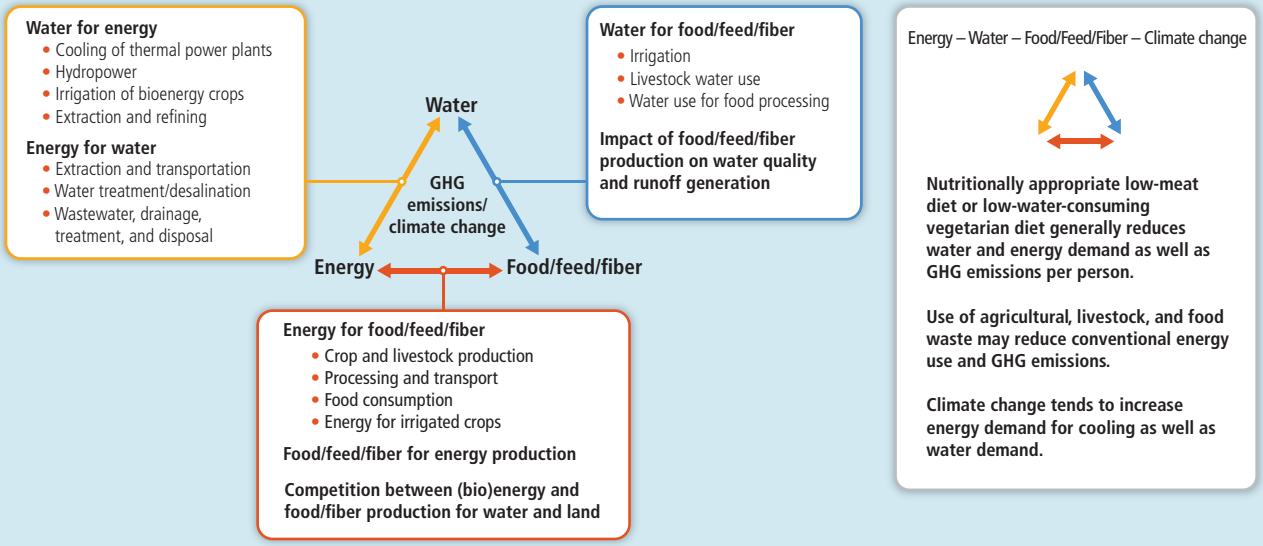
Renewable energy	
Primary objective	Renewable energy production and reduction of emissions
Relevant sectors	Biodiversity, agriculture, food security
Overview	Renewable energy production can require significant land areas and water resources, creating the potential for both positive and negative interactions between mitigation policies and land management. [4.4.4, 13.3.1, 19.3.2, 19.4.1, Box CC-WE]
Examples with interactions	**Central and South America:** Renewable resources, especially hydroelectric power and biofuels, account for substantial fractions of energy production in countries such as Brazil. Where bioenergy crops compete for land with food crops, substantial trade-offs can exist. Land-use change to produce bioenergy can affect food crops, biodiversity, and ecosystem services. Lignocellulosic feedstocks, such as sugarcane second-generation technologies, do not compete with food. [19.3.2, 27.3.6, 27.6.1, Table 27-6] **Australia and New Zealand:** Mandatory renewable energy targets and incentives to increase carbon storage support increased biofuel production and increased biological carbon sequestration, with impacts on biodiversity depending on implementation. Benefits can include reduced erosion, additional habitat, and enhanced connectivity, with risks or lost opportunities associated with large-scale monocultures especially if replacing more diverse landscapes. Large-scale land cover changes can affect catchment yields and regional climate in complex ways. New crops such as oil mallees or other eucalypts may provide multiple benefits, especially in marginal areas, displacing fossil fuels or sequestering carbon, generating income for landholders (essential oils, charcoal, bio-char, biofuels), and providing ecosystem services. [Table 25-7, Box 25-10]
Disaster risk reduction and adaptation to climate extremes	
Primary objective	Increasing resilience to extreme weather events in a changing climate
Relevant sectors	Infrastructure, energy use, spatial planning
Overview	Synergies and tradeoffs among sustainable development, adaptation, and mitigation occur in preparing for and responding to climate extremes and disasters. [13.2 to 13.4, 20.3, 20.4]
Examples with interactions	**Philippines:** The Homeless People's Federation of the Philippines developed responses following disasters, including community-rooted data gathering (e.g., assessing destruction and victims' immediate needs); trust and contact building; savings support; community-organization registration; and identification of needed interventions (e.g., building-materials loans). Community surveys mapped inhabitants especially at risk in informal settlements, raising risk-awareness among the inhabitants and increasing community engagement in planning risk reduction and early warning systems. [8.3.2, 8.4.2] **London:** Within London, built form and other dwelling characteristics can have a stronger influence on indoor temperatures during heat waves than the urban heat island effect, and utilizing shade, thermal mass, ventilation control, and other passive-design features are effective adaptation options. Passive housing designs enhance natural ventilation and improve insulation, while also reducing household emissions. For example, in London the Beddington Zero Energy Development was designed to reduce or eliminate energy demand for heating, cooling, and ventilation for much of the year. [8.3.3, 11.7.4] **United States:** In the United States, post-disaster funds for loss reduction are added to funds provided for disaster recovery. They can be used, for instance, to buy out properties that have experienced repetitive flood losses and relocate residents to safer locations, to elevate structures, to assist communities with purchasing property and altering land-use patterns in flood-prone areas, and to undertake other activities designed to lessen the impacts of future disasters. [14.3.3]

- Geoengineering approaches involving manipulation of the ocean to ameliorate climate change (such as nutrient fertilization, binding of CO_2 by enhanced alkalinity, or direct CO_2 injection into the deep ocean) have very large environmental and associated socioeconomic consequences (*high confidence*). Alternative methods focusing on solar radiation management (SRM) leave ocean acidification unabated as they cannot mitigate rising atmospheric CO_2 emissions. [6.4]
- Some agricultural practices can reduce emissions and also increase resilience of crops to temperature and rainfall variability (*high confidence*). [23.8, Table 25-7]
- Many solutions for reducing energy and water consumption in urban areas with co-benefits for climate change adaptation (e.g., greening cities and recycling water) are already being implemented (*high confidence*). Transport systems promoting active transport and reduced motorized-vehicle use can improve air quality and increase physical activity (*medium confidence*). [11.9, 23.8, 24.4, 26.3, 26.8, Boxes 25-2 and 25-9]
- Improved energy efficiency and cleaner energy sources can lead to reduced emissions of health-damaging climate-altering air pollutants (*very high confidence*). [11.9, 23.8]
- In Africa, experience in implementing integrated adaptation–mitigation responses that leverage developmental benefits encompasses some participation of farmers and local communities in carbon offset systems and increased use of agroforestry and farmer-assisted tree regeneration (*high confidence*). [22.4, 22.6]
- In Asia, development of sustainable cities with fewer fossil-fuel-driven vehicles and with more trees and greenery would have a number of co-benefits, including improved public health (*high confidence*). [24.4 to 24.7]
- In Australasia, transboundary effects from climate change impacts and responses outside Australasia have the potential to outweigh some of the direct impacts within the region, particularly economic impacts on trade-intensive sectors such as agriculture (*medium confidence*) and tourism (*limited evidence*, *high agreement*), but they remain among the least-explored issues. [25.7, 25.9, Box 25-10]
- In North America, policies addressing local concerns (e.g., air pollution, housing for the poor, declines in agricultural production) can be adapted at low or no cost to fulfill adaptation, mitigation, and sustainability goals (*medium confidence*). [26.9]
- In Central and South America, biomass-based renewable energy can impact land use change and deforestation, and could be affected by climate change (*medium confidence*). The expansion of sugarcane, soy, and oil palm may have some effect on land use, leading to deforestation in parts of the Amazon and Central America, among other sub-regions, and to loss of employment in some countries. [27.3]
- For small islands, energy supply and use, tourism infrastructure and activities, and coastal wetlands offer opportunities for adaptation–mitigation synergies (*medium confidence*). [29.6 to 29.8]

Table TS.8 provides further specific examples of interactions among adaptation, mitigation, and sustainable development to complement the assessment findings above.

Box TS.9 | The Water–Energy–Food Nexus

Water, energy, and food/feed/fiber are linked through numerous interactive pathways affected by a changing climate (Box TS.9 Figure 1). [Box CC-WE] The depth and intensity of those linkages vary enormously among countries, regions, and production systems. Many energy sources require significant amounts of water and produce a large quantity of wastewater that requires energy for treatment. [3.7, 7.3, 10.2, 10.3, 22.3, 25.7, Box CC-WE] Food production, refrigeration, transport, and processing also require both energy and water. A major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water, and the sensitivity of precipitation, temperature, and crop yields to climate change (*robust evidence*, *high agreement*). [7.3, Boxes 25-10 and CC-WE]



Box TS.9 Figure 1 | The water–energy–food nexus as related to climate change, with implications for both adaptation and mitigation strategies. [Figure WE-1, Box CC-WE]

Most energy production methods require significant amounts of water, either directly (e.g., crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (*robust evidence*, *high agreement*). [10.2, 10.3, 25.7, Box CC-WE] Water is required for mining, processing, and residue disposal of fossil fuels or their byproducts. [25.7] Water for energy currently ranges from a few percent in most developing countries to more than 50% of freshwater withdrawals in some developed countries, depending on the country. [Box CC-WE] Future water requirements will depend on electric demand growth, the portfolio of generation technologies, and water management options (*medium evidence*, *high agreement*). Future water availability for energy production will change due to climate change (*robust evidence*, *high agreement*). [3.4, 3.5, Box CC-WE]

Energy is also required to supply and treat water. Water may require significant amounts of energy for lifting (especially as aquifers continue to be depleted), transport, and distribution and for its treatment either to use it or to depollute it. Wastewater and even excess rainfall in cities requires energy to be treated or disposed. Some non-conventional water sources (wastewater or seawater) are often highly energy intensive. [Table 25-7, Box 25-2] Energy intensities per cubic meter of water vary by about a factor of 10 among different sources, for example, locally produced potable water from ground/surface water sources versus desalinated seawater. [Boxes 25-2 and CC-WE] Groundwater is generally more energy intensive than surface water. [Box CC-WE]

Linkages among water, energy, food/feed/fiber, and climate are strongly related to land use and management, such as afforestation, which can affect water as well as other ecosystem services, climate, and water cycles (*robust evidence*, *high agreement*). Land degradation often reduces efficiency of water and energy use (e.g., resulting in higher fertilizer demand and surface runoff), and many of these interactions can compromise food security. On the other hand, afforestation activities to sequester carbon have important co-benefits of reducing soil erosion and providing additional (even if only temporary) habitat, but may reduce renewable water resources. [3.7, 4.4, Boxes 25-10 and CC-WE]

Consideration of the interlinkages of energy, food/feed/fiber, water, land use, and climate change has implications for security of supplies of energy, food, and water; adaptation and mitigation pathways; air pollution reduction; and health and economic impacts. This nexus is increasingly recognized as critical to effective climate-resilient-pathway decision making (*medium evidence*, *high agreement*), although tools to support local- and regional-scale assessments and decision support remain very limited.

Working Group II Frequently Asked Questions

These FAQs provide an entry point to the approach and scientific findings of the Working Group II contribution to the Fifth Assessment Report. For summary of the scientific findings, see the Summary for Policymakers (SPM) and Technical Summary (TS). These FAQs, presented in clear and accessible language, do not reflect formal assessment of the degree of certainty in conclusions, and they do not include calibrated uncertainty language presented in the SPM, TS, and underlying chapters. The sources of the relevant assessment in the report are noted by chapter numbers in square brackets.

FAQ 1: Are risks of climate change mostly due to changes in extremes, changes in average climate, or both?

[Chapters 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 18, 19, 22, 23, 24, 25, 26, 27, 28, 29, 30; TS]

People and ecosystems across the world experience climate in many different ways, but weather and climate extremes strongly influence losses and disruptions. Average climate conditions are important. They provide a starting point for understanding what grows where and for informing decisions about tourist destinations, other business opportunities, and crops to plant. But the impacts of a change in average conditions often occur as a result of changes in the frequency, intensity, or duration of extreme weather and climate events. It is the extremes that place excessive and often unexpected demands on systems poorly equipped to deal with those extremes. For example, wet conditions lead to flooding when storm drains and other infrastructure for handling excess water are overwhelmed. Buildings fail when wind speeds exceed design standards. For many kinds of disruption, from crop failure caused by drought to sickness and death from heat waves, the main risks are in the extremes, with changes in average conditions representing a climate with altered timing, intensity, and types of extremes.

FAQ 2: How much can we say about what society will be like in the future, in order to plan for climate change impacts?

[Chapters 1, 2, 14, 15, 16, 17, 20, and 21; TS]

Overall characteristics of societies and economies, such as population size, economic activity, and land use, are highly dynamic. On the scale of just 1 or 2 decades, and sometimes in less time than that, technological revolutions, political movements, or singular events can shape the course of history in unpredictable ways. To understand potential impacts of climate change for societies and ecosystems, scientists use scenarios to explore implications of a range of possible futures. Scenarios are not predictions of what will happen, but they can be useful tools for researching a wide range of "what if" questions about what the world might be like in the future. They can be used to study future emissions of greenhouse gases and climate change. They can also be used to explore the ways climate-change impacts depend on changes in society, such as economic or population growth or progress in controlling diseases. Scenarios of possible decisions and policies can be used to explore the solution space for reducing greenhouse gas emissions and preparing for a changing climate. Scenario analysis creates a foundation for understanding risks of climate change for people, ecosystems, and economies across a range of possible futures. It provides important tools for smart decision making when both uncertainties and consequences are large.

FAQ 3: Why is climate change a particularly difficult challenge for managing risk?

[Chapters 1, 2, 16, 17, 19, 20, 21, and 25; TS]

Risk management is easier for nations, companies, and even individuals when the likelihood and consequences of possible events are readily understood. Risk management becomes much more challenging when the stakes are higher or when uncertainty is greater. As the WGII AR5 demonstrates, we know a great deal about the impacts of climate change that have already occurred, and we understand a great deal about expected impacts in the future. But many uncertainties remain, and will persist. In particular, future greenhouse gas emissions depend on societal choices, policies, and technology advancements not yet made, and climate-change impacts depend on both the amount of climate change that occurs and the effectiveness of development in reducing exposure and vulnerability. The real challenge of dealing effectively with climate change is recognizing the value of wise and timely decisions in a setting where complete knowledge is impossible. This is the essence of risk management.

FAQ 4: What are the timeframes for mitigation and adaptation benefits?

[Chapters 1, 2, 16, 19, 20, and 21; TS]

Adaptation can reduce damage from impacts that cannot be avoided. Mitigation strategies can decrease the amount of climate change that occurs, as summarized in the WGIII AR5. But the consequences of investments in mitigation emerge over time. The constraints of existing infrastructure, limited deployment of many clean technologies, and the legitimate aspirations for economic growth around the world all tend to slow the deviation from established trends in greenhouse gas emissions. Over the next few decades, the climate change we experience will be determined primarily by the combination of past actions and current trends. The near-term is thus an era where short-term risk reduction comes from adapting to the changes already underway. Investments in mitigation during both the near-term and the longer-term do, however, have substantial leverage on the magnitude of climate change in the latter decades of the century, making the second half of the 21st century and beyond an era of climate options. Adaptation will still be important during the era of climate options, but with opportunities and needs that will depend on many aspects of climate change and development policy, both in the near term and in the long term.

FAQ 5: Can science identify thresholds beyond which climate change is dangerous?

[Chapters 1, 2, 4, 5, 6, 16, 17, 18, 19, 20, and 25; TS]

Human activities are changing the climate. Climate-change impacts are already widespread and consequential. But while science can quantify climate change risks in a technical sense, based on the probability, magnitude, and nature of the potential consequences of climate change, determining what is dangerous is ultimately a judgment that depends on values and objectives. For example, individuals will value the present versus the future differently and will bring personal worldviews on the importance of assets like biodiversity, culture, and aesthetics. Values also influence judgments about the relative importance of global economic growth versus assuring the well-being of the most vulnerable among us. Judgments about dangerousness can depend on the extent to which one's livelihood, community, and family are directly exposed and vulnerable to climate change. An individual or community displaced

by climate change might legitimately consider that specific impact dangerous, even though that single impact might not cross the global threshold of dangerousness. Scientific assessment of risk can provide an important starting point for such value judgments about the danger of climate change.

FAQ 6: Are we seeing impacts of recent climate change?

[Chapters 3, 4, 5, 6, 7, 11, 13, 18, 22, 23, 24, 25, 26, 27, 28, 29, and 30; SPM]

Yes, there is strong evidence of impacts of recent observed climate change on physical, biological, and human systems. Many regions have experienced warming trends and more frequent high-temperature extremes. Rising temperatures are associated with decreased snowpack, and many ecosystems are experiencing climate-induced shifts in the activity, range, or abundance of the species that inhabit them. Oceans are also displaying changes in physical and chemical properties that, in turn, are affecting coastal and marine ecosystems such as coral reefs, and other oceanic organisms such as mollusks, crustaceans, fishes, and zooplankton. Crop production and fishery stocks are sensitive to changes in temperature. Climate change impacts are leading to shifts in crop yields, decreasing yields overall and sometimes increasing them in temperate and higher latitudes, and catch potential of fisheries is increasing in some regions but decreasing in others. Some indigenous communities are changing seasonal migration and hunting patterns to adapt to changes in temperature.

FAQ 7: Are the future impacts of climate change only negative? Might there be positive impacts as well?

[Chapters 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 19, 22, 23, 24, 25, 26, 27, and 30]

Overall, the report identifies many more negative impacts than positive impacts projected for the future, especially for high magnitudes and rates of climate change. Climate change will, however, have different impacts on people around the world and those effects will vary not only by region but over time, depending on the rate and magnitude of climate change. For example, many countries will face increased challenges for economic development, increased risks from some diseases, or degraded ecosystems, but some countries will probably have increased opportunities for economic development, reduced instances of some diseases, or expanded areas of productive land. Crop yield changes will vary with geography and by latitude. Patterns of potential catch for fisheries are changing globally as well, with both positive and negative consequences. Availability of resources such as usable water will also depend on changing rates of precipitation, with decreased availability in many places but possible increases in runoff and groundwater recharge in some regions like the high latitudes and wet tropics.

FAQ 8: What communities are most vulnerable to the impacts of climate change?

[Chapters 8, 9, 12, 13, 19, 22, 23, 26, 27, 29, and Box CC-GC]

Every society is vulnerable to the impacts of climate change, but the nature of that vulnerability varies across regions and communities, over time, and depends on unique socioeconomic and other conditions. Poorer communities tend to be more vulnerable to loss of health and life, while wealthier communities usually have more economic assets at risk. Regions affected by violence or governance failure can be particularly vulnerable to climate change impacts. Development challenges, such as gender inequality and low levels of education, and other differences among communities in age, race and ethnicity, socioeconomic status, and governance can influence vulnerability to climate change impacts in complex ways.

FAQ 9: Does climate change cause violent conflicts?

[Chapters 12, 19]

Some factors that increase risks from violent conflicts and civil wars are sensitive to climate change. For example, there is growing evidence that factors like low per capita incomes, economic contraction, and inconsistent state institutions are associated with the incidence of civil wars, and also seem to be sensitive to climate change. Climate-change policies, particularly those associated with changing rights to resources, can also increase risks from violent conflict. While statistical studies document a relationship between climate variability and conflict, there remains much disagreement about whether climate change directly causes violent conflicts.

FAQ 10: How are adaptation, mitigation, and sustainable development connected?

[Chapters 1, 2, 8, 9, 10, 11, 13, 17, 20, 22, 23, 24, 25, 26, 27, and 29]

Mitigation has the potential to reduce climate change impacts, and adaptation can reduce the damage of those impacts. Together, both approaches can contribute to the development of societies that are more resilient to the threat of climate change and therefore more sustainable. Studies indicate that interactions between adaptation and mitigation responses have both potential synergies and tradeoffs that vary according to context. Adaptation responses may increase greenhouse gas emissions (e.g., increased fossil-based air conditioning in response to higher temperatures), and mitigation may impede adaptation (e.g., increased use of land for bioenergy crop production negatively impacting ecosystems). There are growing examples of co-benefits of mitigation and development policies, like those which can potentially reduce local emissions of health-damaging and climate-altering air pollutants from energy systems. It is clear that adaptation, mitigation, and sustainable development will be connected in the future.

FAQ 11: Why is it difficult to be sure of the role of climate change in observed effects on people and ecosystems?

[Chapter 3, 4, 5, 6, 7, 11, 12, 13, 18, 22, 23, 24, 25, 26, 27, 28, 29, and 30]

Climate change is one of many factors impacting the Earth's complex human societies and natural ecosystems. In some cases the effect of climate change has a unique pattern in space or time, providing a fingerprint for identification. In others, potential effects of climate change are thoroughly mixed with effects of land use change, economic development, changes in technology, or other processes. Trends in human activities, health, and society often have many simultaneous causes, making it especially challenging to isolate the role of climate change.

Much climate-related damage results from extreme weather events and could be affected by changes in the frequency and intensity of these events due to climate change. The most damaging events are rare, and the level of damage depends on context. It can therefore be challenging to build statistical confidence in observed trends, especially over short time periods. Despite this, many climate change impacts on the physical environment and ecosystems have been identified, and increasing numbers of impacts have been found in human systems as well.

Cross-Chapter Boxes

CR

Coral Reefs

Jean-Pierre Gattuso (France), Ove Hoegh-Guldberg (Australia), Hans-Otto Pörtner (Germany)

Coral reefs are shallow-water ecosystems that consist of reefs made of calcium carbonate which is mostly secreted by reef-building corals and encrusting macroalgae. They occupy less than 0.1% of the ocean floor yet play multiple important roles throughout the tropics, housing high levels of biological diversity as well as providing key ecosystem goods and services such as habitat for fisheries, coastal protection, and appealing environments for tourism (Wild et al., 2011). About 275 million people live within 30 km of a coral reef (Burke et al., 2011) and derive some benefits from the ecosystem services that coral reefs provide (Hoegh-Guldberg, 2011), including provisioning (food, livelihoods, construction material, medicine), regulating (shoreline protection, water quality), supporting (primary production, nutrient cycling), and cultural (religion, tourism) services. This is especially true for the many coastal and small island nations in the world's tropical regions (Section 29.3.3.1).

Coral reefs are one of the most vulnerable marine ecosystems (*high confidence*; Sections 5.4.2.4, 6.3.1, 6.3.2, 6.3.5, 25.6.2, and 30.5), and more than half of the world's reefs are under medium or high risk of degradation (Burke et al., 2011). Most human-induced disturbances to coral reefs were local until the early 1980s (e.g., unsustainable coastal development, pollution, nutrient enrichment, and overfishing) when disturbances from ocean warming (principally mass coral bleaching and mortality) began to become widespread (Glynn, 1984). Concern about the impact of ocean acidification on coral reefs developed over the same period, primarily over the implications of ocean acidification for the building and maintenance of the calcium carbonate reef framework (Box CC-OA).

A wide range of climatic and non-climatic drivers affect corals and coral reefs and negative impacts have already been observed (Sections 5.4.2.4, 6.3.1, 6.3.2, 25.6.2.1, 30.5.3, 30.5.6). Bleaching involves the breakdown and loss of endosymbiotic algae, which live in the coral tissues and play a key role in supplying the coral host with energy (see Section 6.3.1. for physiological details and Section 30.5 for a regional analysis). Mass coral bleaching and mortality, triggered by positive temperature anomalies (*high confidence*), is the most widespread and conspicuous impact of climate change (Figure CR-1A and B, Figure 5-3; Sections 5.4.2.4, 6.3.1, 6.3.5, 25.6.2.1, 30.5, and 30.8.2). For example, the level of thermal stress at most of the 47 reef sites where bleaching occurred during 1997–1998 was unmatched in the period 1903–1999 (Lough, 2000). Ocean acidification reduces biodiversity (Figure CR-1C and D) and the calcification rate of corals (*high confidence*; Sections 5.4.2.4, 6.3.2, 6.3.5) while at the same time increasing the rate of dissolution of the reef framework (*medium confidence*; Section 5.2.2.4) through stimulation of biological erosion and chemical dissolution. Taken together, these changes will tip the calcium carbonate balance of coral reefs toward net dissolution (*medium confidence*; Section 5.4.2.4).

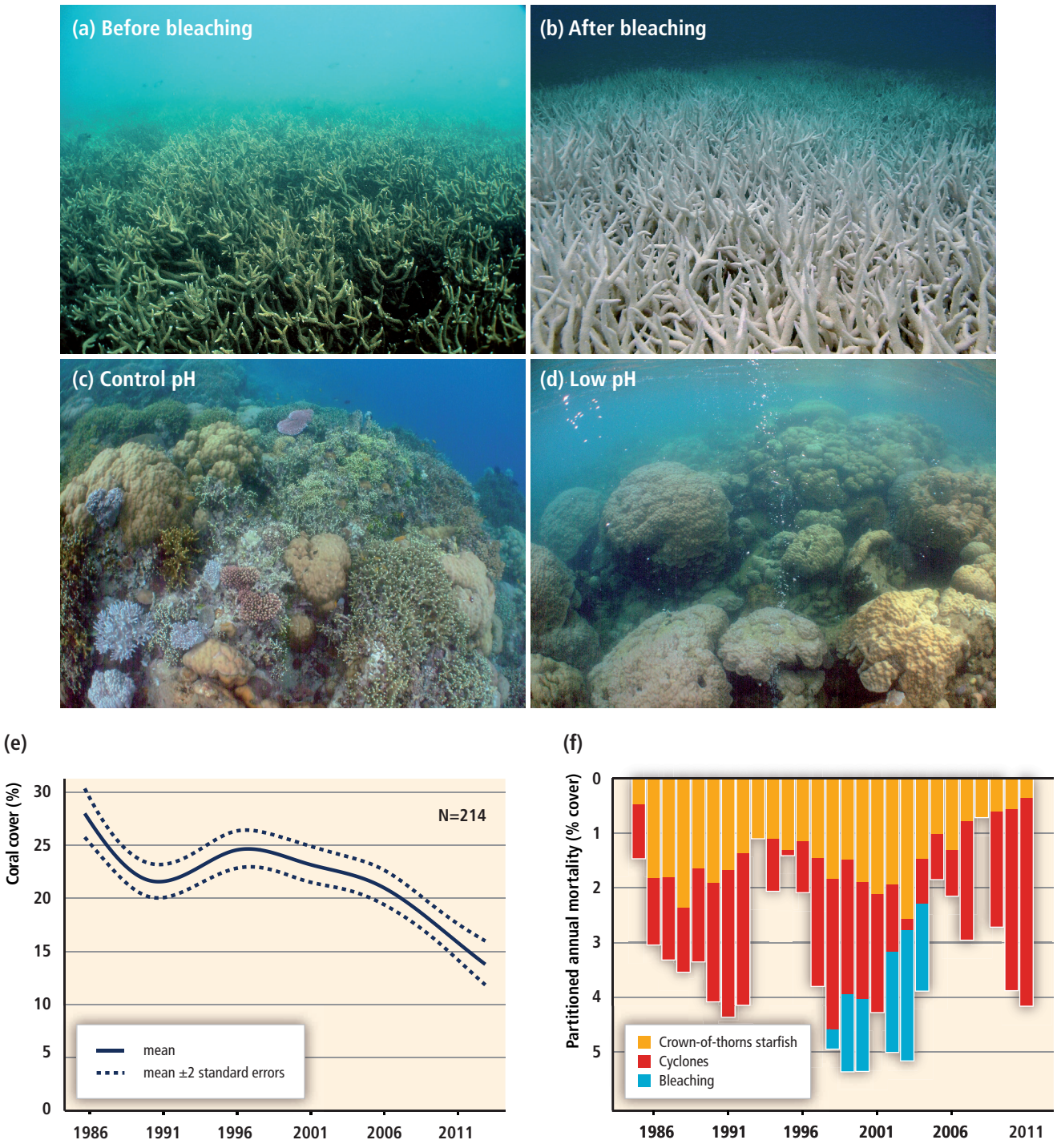


Figure CR-1 | (a, b) The same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Approximately 95% of the coral community was severely bleached in 2002 (Elvidge et al., 2004). Corals experience increasing mortality as the intensity of a heating event increases. A few coral species show the ability to shuffle symbiotic communities of dinoflagellates and appear to be more tolerant of warmer conditions (Berkelmans and van Oppen, 2006; Jones et al., 2008). (c, d) Three CO_2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO_2 is related to fundamental changes in the ecology of coral reefs (Fabricius et al., 2011), including reduced coral diversity (–39%), severely reduced structural complexity (–67%), lower density of young corals (–66%), and fewer crustose coralline algae (–85%). At high CO_2 sites (d; median pH_T ~7.8, where pH_T is pH on the total scale), reefs are dominated by massive corals while corals with high morphological complexity are underrepresented compared with control sites (c; median pH_T ~8.0). Reef development ceases at pH_T values below 7.7. (e) Temporal trend in coral cover for the whole Great Barrier Reef over the period 1985–2012 (N=number of reefs, De'ath et al., 2012). (f) Composite bars indicate the estimated mean coral mortality for each year, and the sub-bars indicate the relative mortality due to crown-of-thorns starfish, cyclones, and bleaching for the whole Great Barrier Reef (De'ath et al., 2012). (Photo credit: R. Berkelmans (a and b) and K. Fabricius (c and d).)

Ocean warming and acidification have synergistic effects in several reef-builders (Section 5.2.4.2, 6.3.5). Taken together, these changes will erode habitats for reef-based fisheries, increase the exposure of coastlines to waves and storms, as well as degrading environmental features important to industries such as tourism (*high confidence*; Section 6.4.1.3, 25.6.2, 30.5).

A growing number of studies have reported regional scale changes in coral calcification and mortality that are consistent with the scale and impact of ocean warming and acidification when compared to local factors such as declining water quality and overfishing (Hoegh-Guldberg et al., 2007). The abundance of reef building corals is in rapid decline in many Pacific and Southeast Asian regions (*very high confidence*, 1 to 2% per year for 1968–2004; Bruno and Selig, 2007). Similarly, the abundance of reef-building corals has decreased by more than 80% on many Caribbean reefs (1977–2001; Gardner et al., 2003), with a dramatic phase shift from corals to seaweeds occurring on Jamaican reefs (Hughes, 1994). Tropical cyclones, coral predators, and thermal stress-related coral bleaching and mortality have led to a decline in coral cover on the Great Barrier Reef by about 51% between 1985 and 2012 (Figure CR-1E and F). Although less well documented, benthic invertebrates other than corals are also at risk (Przeslawski et al., 2008). Fish biodiversity is threatened by the permanent degradation of coral reefs, including in a marine reserve (Jones et al., 2004).

Future impacts of climate-related drivers (ocean warming, acidification, sea level rise as well as more intense tropical cyclones and rainfall events) will exacerbate the impacts of non-climate–related drivers (*high confidence*). Even under optimistic assumptions regarding corals being able to rapidly adapt to thermal stress, one-third (9 to 60%, 68% uncertainty range) of the world's coral reefs are projected to be subject to long-term degradation (next few decades) under the Representative Concentration Pathway (RCP)3-PD scenario (Frieler et al., 2013). Under the RCP4.5 scenario, this fraction increases to two-thirds (30 to 88%, 68% uncertainty range). If present-day corals have residual capacity to acclimate and/or adapt, half of the coral reefs may avoid high-frequency bleaching through 2100 (*limited evidence*, *limited agreement*; Logan et al., 2014). Evidence of corals adapting rapidly, however, to climate change is missing or equivocal (Hoegh-Guldberg, 2012).

Damage to coral reefs has implications for several key regional services:

- *Resources*: Coral reefs account for 10 to 12% of the fish caught in tropical countries, and 20 to 25% of the fish caught by developing nations (Garcia and de Leiva Moreno, 2003). More than half (55%) of the 49 island countries considered by Newton et al. (2007) are already exploiting their coral reef fisheries in an unsustainable way and the production of coral reef fish in the Pacific is projected to decrease 20% by 2050 under the Special Report on Emission Scenarios (SRES) A2 emissions scenario (Bell et al., 2013).
- *Coastal protection*: Coral reefs contribute to protecting the shoreline from the destructive action of storm surges and cyclones (Sheppard et al., 2005), sheltering the only habitable land for several island nations, habitats suitable for the establishment and maintenance of mangroves and wetlands, as well as areas for recreational activities. This role is threatened by future sea level rise, the decrease in coral cover, reduced rates of calcification, and higher rates of dissolution and bioerosion due to ocean warming and acidification (Sections 5.4.2.4, 6.4.1, 30.5).
- *Tourism*: More than 100 countries benefit from the recreational value provided by their coral reefs (Burke et al., 2011). For example, the Great Barrier Reef Marine Park attracts about 1.9 million visits each year and generates A$5.4 billion to the Australian economy and 54,000 jobs (90% in the tourism sector; Biggs, 2011).

Coral reefs make a modest contribution to the global gross domestic product (GDP) but their economic importance can be high at the country and regional scales (Pratchett et al., 2008). For example, tourism and fisheries represent 5% of the GDP of South Pacific islands (average for 2001–2011; Laurans et al., 2013). At the local scale, these two services provided in 2009–2011 at least 25% of the annual income of villages in Vanuatu and Fiji (Pascal, 2011; Laurans et al., 2013).

Isolated reefs can recover from major disturbance, and the benefits of their isolation from chronic anthropogenic pressures can outweigh the costs of limited connectivity (Gilmour et al., 2013). Marine protected areas (MPAs) and fisheries management have the potential to increase ecosystem resilience and increase the recovery of coral reefs after climate change impacts such as mass coral bleaching (McLeod et al., 2009). Although they are key conservation and management tools, they are unable to protect corals directly from thermal stress (Selig et al., 2012), suggesting that they need to be complemented with additional and alternative strategies (Rau et al., 2012; Billé et al., 2013). While MPA networks are a critical management tool, they should be established considering other forms of resource management (e.g., fishery catch limits and gear restrictions) and integrated ocean and coastal management to control land-based threats such as pollution and sedimentation. There is *medium confidence* that networks of highly protected areas nested within a broader management framework can contribute to preserving coral reefs under increasing human pressure at local and global scales (Salm et al., 2006). Locally, controlling the input of nutrients and sediment from land is an important complementary management strategy (Mcleod et al., 2009) because nutrient enrichment can increase the susceptibility of corals to bleaching (Wiedenmann et al., 2013) and coastal pollutants enriched with fertilizers can increase acidification (Kelly et al., 2011). In the long term, limiting the amount of ocean warming and acidification is central to ensuring the viability of coral reefs and dependent communities (*high confidence*; Section 5.2.4.4, 30.5).

References

Bell, J.D., A. Ganachaud, P.C. Gehrke, S.P. Griffiths, A.J. Hobday, O. Hoegh-Guldberg, J.E. Johnson, R. Le Borgne, P. Lehodey, J.M. Lough, R.J. Matear, T.D. Pickering, M.S. Pratchett, A. Sen Gupta, I. Senina and M. Waycott, 2013: Mixed responses of tropical Pacific fisheries and aquaculture to climate change. *Nature Climate Change*, **3**(**6**), 591-599.

Berkelmans, R. and M.J.H. van Oppen, 2006: The role of zooxanthellae in the thermal tolerance of corals: a 'nugget of hope' for coral reefs in an era of climate change. *Proceedings of the Royal Society B: Biological Sciences*, **273**(**1599**), 2305-2312.

Biggs, D., 2011: *Case study: the resilience of the nature-based tourism system on Australia's Great Barrier Reef*. Report prepared for the Australian Government Department of Sustainability Environment Water Population and Communities on behalf of the State of the Environment 2011 Committee, Canberra, 32 pp.
Billé, R., R. Kelly, A. Biastoch, E. Harrould-Kolieb, D. Herr, F. Joos, K.J. Kroeker, D. Laffoley, A. Oschlies and J.-P. Gattuso, 2013: Taking action against ocean acidification: a review of management and policy options. *Environmental Management*, **52**, 761-779.
Bruno, J.F. and E.R. Selig, 2007: Regional decline of coral cover in the Indo-Pacific: timing, extent, and subregional comparisons. PLoS ONE, 2(8), e711. doi: 10.1371/journal.pone.0000711.
Burke, L., K. Reytar, M. Spalding and A. Perry, 2011: *Reefs at risk revisited*. World Resources Institute, Washington D.C., 114 pp.
De'ath, G., K.E. Fabricius, H. Sweatman and M. Puotinen, 2012: The 27-year decline of coral cover on the Great Barrier Reef and its causes. *Proceedings of the National Academy of Sciences of the United States of America*, **109**(**44**), 17995-17999.
Elvidge, C.D., J.B. Dietz, R. Berkelmans, S. Andréfouët, W. Skirving, A.E. Strong and B.T. Tuttle, 2004: Satellite observation of Keppel Islands (Great Barrier Reef) 2002 coral bleaching using IKONOS data. *Coral Reefs*, **23**(**1**), 123-132.
Fabricius, K.E., C. Langdon, S. Uthicke, C. Humphrey, S. Noonan, G. De'ath, R. Okazaki, N. Muehllehner, M.S. Glas and J.M. Lough, 2011: Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations. *Nature Climate Change*, **1**(**3**), 165-169.
Frieler, K., M. Meinshausen, A. Golly, M. Mengel, K. Lebek, S.D. Donner and O. Hoegh-Guldberg, 2013: Limiting global warming to 2°C is unlikely to save most coral reefs. *Nature Climate Change*, **3**(**2**), 165-170.
Garcia, S.M. and I. de Leiva Moreno, 2003: Global overview of marine fisheries. In: *Responsible Fisheries in the Marine Ecosystem* [Sinclair, M. and G. Valdimarsson (eds.)]. Wallingford: CABI, pp. 1-24.
Gardner, T.A., I.M. Côté, J.A. Gill, A. Grant and A.R. Watkinson, 2003: Long-term region-wide declines in Caribbean corals. *Science*, **301**(**5635**), 958-960.
Gilmour, J.P., L.D. Smith, A.J. Heyward, A.H. Baird and M.S. Pratchett, 2013: Recovery of an isolated coral reef system following severe disturbance. *Science*, **340**(**6128**), 69-71.
Glynn, P.W., 1984: Widespread coral mortality and the 1982-83 El Niño warming event. *Environmental Conservation*, **11**(**2**), 133-146.
Hoegh-Guldberg, O., 2011: Coral reef ecosystems and anthropogenic climate change. *Regional Environmental Change*, **11**, 215-227.
Hoegh-Guldberg, O., 2012: The adaptation of coral reefs to climate change: Is the Red Queen being outpaced? *Scientia Marina*, **76**(**2**), 403-408.
Hoegh-Guldberg, O., P.J. Mumby, A.J. Hooten, R.S. Steneck, P. Greenfield, E. Gomez, C.D. Harvell, P.F. Sale, A.J. Edwards, K. Caldeira, N. Knowlton, C.M. Eakin, R. Iglesias-Prieto, N. Muthiga, R.H. Bradbury, A. Dubi and M.E. Hatziolos, 2007: Coral reefs under rapid climate change and ocean acidification. *Science*, **318**(**5857**), 1737-1742.
Hughes, T.P., 1994: Catastrophes, phase-shifts, and large-scale degradation of a Caribbean coral reef. *Science*, **265**(**5178**), 1547-1551.
Jones, A.M., R. Berkelmans, M.J.H. van Oppen, J.C. Mieog and W. Sinclair, 2008: A community change in the algal endosymbionts of a scleractinian coral following a natural bleaching event: field evidence of acclimatization. Proceedings of the *Royal Society B: Biological Sciences*, **275**(**1641**), 1359-1365.
Jones, G.P., M.I. McCormick, M. Srinivasan and J.V. Eagle, 2004: Coral decline threatens fish biodiversity in marine reserves. *Proceedings of the National Academy of Sciences of the United States of America*, **101**(**21**), 8251-8253.
Kelly, R.P., M.M. Foley, W.S. Fisher, R.A. Feely, B.S. Halpern, G.G. Waldbusser and M.R. Caldwell, 2011: Mitigating local causes of ocean acidification with existing laws. *Science*, **332**(**6033**), 1036-1037.
Laurans, Y., N. Pascal, T. Binet, L. Brander, E. Clua, G. David, D. Rojat and A. Seidl, 2013: Economic valuation of ecosystem services from coral reefs in the South Pacific: taking stock of recent experience. *Journal of Environmental Management*, **116**, 135-144.
Logan, C.A., J.P. Dunne, C.M. Eakin and S.D. Donner, 2014: Incorporating adaptive responses into future projections of coral bleaching. *Global Change Biology*, **20**(**1**), 125-139.
Lough, J.M., 2000: 1997–98: Unprecedented thermal stress to coral reefs? *Geophysical Research Letters*, **27**(**23**), 3901-3904.
McLeod, E., R. Salm, A. Green and J. Almany, 2009: Designing marine protected area networks to address the impacts of climate change. *Frontiers in Ecology and the Environment*, **7**(**7**), 362-370.
Newton, K., I.M. Côté, G.M. Pilling, S. Jennings and N.K. Dulvy, 2007: Current and future sustainability of island coral reef fisheries. *Current Biology*, **17**(**7**), 655-658.
Pascal, N., 2011: *Cost-benefit analysis of community-based marine protected areas: 5 case studies in Vanuatu, South Pacific*. CRISP Research Reports. CRIOBE (EPHE/CNRS). Insular Research Center and Environment Observatory, Mooréa, French Polynesia, 107 pp.
Pratchett, M.S., P.L. Munday, S.K. Wilson, N.A.J. Graham, J.E. Cinner, D.R. Bellwood, G.P. Jones, N.V.C. Polunin and T.R. McClanahan, 2008: Effects of climate-induced coral bleaching on coral-reef fishes - Ecological and economic consequences. *Oceanography and Marine Biology: An Annual Review*, **46**, 251-296.
Przeslawski, R., S. Ahyong, M. Byrne, G. Wörheide and P. Hutchings, 2008: Beyond corals and fish: the effects of climate change on noncoral benthic invertebrates of tropical reefs. *Global Change Biology*, **14**(**12**), 2773-2795.
Rau, G.H., E.L. McLeod and O. Hoegh-Guldberg, 2012: The need for new ocean conservation strategies in a high-carbon dioxide world. *Nature Climate Change*, **2**(**10**), 720-724.
Salm, R.V., T. Done and E. McLeod, 2006: Marine Protected Area planning in a changing climate. In: *Coastal and Estuarine Studies 61. Coral Reefs and Climate Change: Science and Management*. [Phinney, J.T., O. Hoegh-Guldberg, J. Kleypas, W. Skirving and A. Strong (eds.)]. American Geophysical Union, pp. 207-221.
Selig, E.R., K.S. Casey and J.F. Bruno, 2012: Temperature-driven coral decline: the role of marine protected areas. *Global Change Biology*, **18**(**5**), 1561-1570.
Sheppard, C., D.J. Dixon, M. Gourlay, A. Sheppard and R. Payet, 2005: Coral mortality increases wave energy reaching shores protected by reef flats: Examples from the Seychelles. *Estuarine, Coastal and Shelf Science*, **64**(**2-3**), 223-234.
Wiedenmann, J., C. D'Angelo, E.G. Smith, A.N. Hunt, F.-E. Legiret, A.D. Postle and E.P. Achterberg, 2013: Nutrient enrichment can increase the susceptibility of reef corals to bleaching. *Nature Climate Change*, **3**(**2**), 160-164.
Wild, C., O. Hoegh-Guldberg, M.S. Naumann, M.F. Colombo-Pallotta, M. Ateweberhan, W.K. Fitt, R. Iglesias-Prieto, C. Palmer, J.C. Bythell, J.-C. Ortiz, Y. Loya and R. van Woesik, 2011: Climate change impedes scleractinian corals as primary reef ecosystem engineers. *Marine and Freshwater Research*, **62**(**2**), 205-215.

This cross-chapter box should be cited as:
Gattuso, J.-P., O. Hoegh-Guldberg, and H.-O. Pörtner, 2014: Cross-chapter box on coral reefs. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 97-100.

EA

Ecosystem-Based Approaches to Adaptation—Emerging Opportunities

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Ecosystem-based adaptation (EBA), defined as the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change (CBD, 2009), integrates the use of biodiversity and ecosystem services into climate change adaptation strategies (e.g., CBD, 2009; Munroe et al., 2011; see IPCC AR5 WGII Chapters 3, 4, 5, 8, 9, 13, 14, 15, 16, 19, 22, 25, and 27). EBA is implemented through the sustainable management of natural resources and conservation and restoration of ecosystems, to provide and sustain services that facilitate adaptation both to climate variability and change (Colls et al., 2009). It also sets out to take into account the multiple social, economic, and cultural co-benefits for local communities (CBD COP 10 Decision X/33).

EBA can be combined with, or even serve as a substitute for, the use of engineered infrastructure or other technological approaches. Engineered defenses such as dams, sea walls, and levees adversely affect biodiversity, potentially resulting in maladaptation due to damage to ecosystem regulating services (Campbell et al., 2009; Munroe et al., 2011). There is some evidence that the restoration and use of ecosystem services may reduce or delay the need for these engineering solutions (CBD, 2009). EBA offers lower risk of maladaptation than engineering solutions in that their application is more flexible and responsive to unanticipated environmental changes. Well-integrated EBA can be more cost effective and sustainable than non-integrated physical engineering approaches (Jones et al., 2012), and may contribute to achieving sustainable development goals (e.g., poverty reduction, sustainable environmental management, and even mitigation objectives), especially when they are integrated with sound ecosystem management approaches (CBD, 2009). In addition, EBA yields economic, social, and environmental co-benefits in the form of ecosystem goods and services (World Bank, 2009).

EBA is applicable in both developed and developing countries. In developing countries where economies depend more directly on the provision of ecosystem services (Vignola et al., 2009), EBA may be a highly useful approach to reduce risks to climate change impacts and ensure that development proceeds on a pathways that are resilient to climate change (Munang et al., 2013). EBA projects may be developed by enhancing existing initiatives, such as community-based adaptation and natural resource management approaches (e.g., Khan et al., 2012, Midgley et al., 2012; Roberts et al., 2012).

Examples of ecosystem based approaches to adaptation include:

- Sustainable water management, where river basins, aquifers, flood plains, and their associated vegetation are managed or restored to provide resilient water storage and

enhanced baseflows, flood regulation and protection services, reduction of erosion/siltation rates, and more ecosystem goods (e.g., Opperman et al., 2009; Midgley et al., 2012)
- Disaster risk reduction through the restoration of coastal habitats (e.g., mangroves, wetlands, and deltas) to provide effective measure against storm-surges, saline intrusion, and coastal erosion (Jonkman et al., 2013)
- Sustainable management of grasslands and rangelands to enhance pastoral livelihoods and increase resilience to drought and flooding
- Establishment of diverse and resilient agricultural systems, and adapting crop and livestock variety mixes to secure food provision. Traditional knowledge may contribute in this area through, for example, identifying indigenous crop and livestock genetic diversity, and water conservation techniques.
- Management of fire-prone ecosystems to achieve safer fire regimes while ensuring the maintenance of natural processes

Application of EBA, like other approaches, is not without risk, and risk/benefit assessments will allow better assessment of opportunities offered by the approach (CBD, 2009). The examples of EBA are too few and too recent to assess either the risks or the benefits comprehensively at this stage. EBA is still a developing concept but should be considered alongside adaptation options based more on engineering works or social change, and existing and new cases used to build understanding of when and where its use is appropriate.

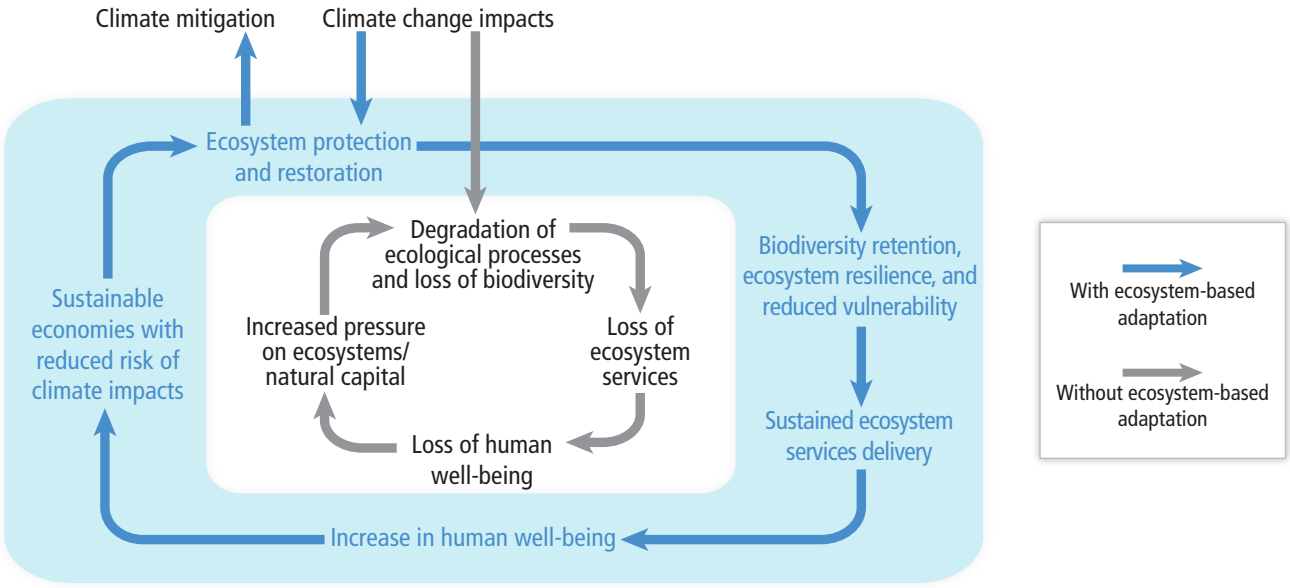

Figure EA-1 | Adapted from Munang et al. (2013). Ecosystem-based adaptation (EBA) uses the capacity of nature to buffer human systems from the adverse impacts of climate change. Without EBA, climate change may cause degradation of ecological processes (central white panel) leading to losses in human well-being. Implementing EBA (outer blue panel) may reduce or offset these adverse impacts resulting in a virtuous cycle that reduces climate-related risks to human communities, and may provide mitigation benefits.

References

Campbell, A., V. Kapos, J. Scharlemann, P. Bubb, A. Chenery, L. Coad, B. Dickson, N. Doswald, M. Khan, F. Kershaw, and M. Rashid, 2009: *Review of the Literature on the Links between Biodiversity and Climate Change: Impacts, Adaptation and Mitigation*. CBD Technical Series No. 42, Secretariat of the Convention on Biological Diversity (CBD), Montreal, QC, Canada, 124 pp.

CBD, 2009: *Connecting Biodiversity and Climate Change Mitigation and Adaptation: Report of the Second Ad Hoc Technical Expert Group on Biodiversity and Climate Change*. CBD Technical Series No. 41, Secretariat of the Convention on Biological Diversity (CBD), Montreal, QC, Canada, 126 pp.

Colls, A., N. Ash, and N. Ikkala, 2009: *Ecosystem-Based Adaptation: A Natural Response to Climate Change*. International Union for Conservation of Nature and Natural Resources (IUCN), Gland, Switzerland, 16 pp.

Jones, H.P., D.G. Hole, and E.S. Zavaleta, 2012: Harnessing nature to help people adapt to climate change. *Nature Climate Change*, **2**(**7**), 504-509.

Jonkman, S.N., M.M. Hillen, R.J. Nicholls, W. Kanning, and M. van Ledden, 2013: Costs of adapting coastal defences to sea-level rise – new estimates and their implications. *Journal of Coastal Research*, **29**(**5**), 1212-1226.

Khan, A.S., A. Ramachandran, N. Usha, S. Punitha, and V. Selvam, 2012: Predicted impact of the sea-level rise at Vellar-Coleroon estuarine region of Tamil Nadu coast in India: mainstreaming adaptation as a coastal zone management option. *Ocean & Coastal Management*, 69, 327-339.

Midgley, G.F., S. Marais, M. Barnett, and K. Wågsæther, 2012: *Biodiversity, Climate Change and Sustainable Development – Harnessing Synergies and Celebrating Successes*. Final Technical Report, The Adaptation Network Secretariat, hosted by Indigo Development & Change and The Environmental Monitoring Group, Nieuwoudtville, South Africa. 70 pp.

Munang, R, I. Thiaw, K. ALverson, M. Mumba, J. Liu, and M. Rivington, 2013: Climate change and ecosystem-based adaptation: a new pragmatic approach to buffering climate change impacts. *Current Opinion in Environmental Sustainability*, **5**(**1**), 67-71.

Munroe, R., N. Doswald, D. Roe, H. Reid, A. Giuliani, I. Castelli, and I. Moller, 2011: *Does EbA Work? A Review of the Evidence on the Effectiveness of Ecosystem-Based Approaches to Adaptation*. Research collaboration between BirdLife International, United Nations Environment Programme-World Conservation Monitoring Centre (UNEP-WCMC), and the University of Cambridge, Cambridge, UK, and the International Institute for Environment and Development (IIED), London, UK, 4 pp.

Opperman, J.J., G.E. Galloway, J. Fargione, J.F. Mount, B.D. Richter, and S. Secchi, 2009: Sustainable floodplains through large-scale reconnection to rivers. *Science*, **326**(**5959**), 1487-1488.

Roberts, D., R. Boon, N. Diederichs, E. Douwes, N. Govender, A. McInnes, C. McLean, S. O'Donoghue, and M. Spires, 2012: Exploring ecosystem-based adaptation in Durban, South Africa: "learning-by-doing" at the local government coal face. *Environment and Urbanization*, **24**(**1**), 167-195.

Vignola, R., B. Locatelli, C. Martinez, and P. Imbach, 2009: Ecosystem-based adaptation to climate change: what role for policymakers, society and scientists? *Mitigation and Adaptation Strategies for Global Change*, **14**(**8**), 691-696.

This cross-chapter box should be cited as:

Shaw, M.R., J.T. Overpeck, and G.F. Midgley, 2014: Cross-chapter box on ecosystem based approaches to adaptation—emerging opportunities. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 101-103.

GC

Gender and Climate Change

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Gender, along with sociodemographic factors of age, wealth, and class, is critical to the ways in which climate change is experienced. There are significant gender dimensions to impacts, adaptation, and vulnerability. This issue was raised in WGII AR4 and SREX reports (Adger et al., 2007; IPCC, 2012), but for the AR5 there are significant new findings, based on multiple lines of evidence on how climate change is differentiated by gender, and how climate change contributes to perpetuating existing gender inequalities. This new research has been undertaken in every region of the world (e.g. Brouwer et al., 2007; Buechler, 2009; Nelson and Stathers, 2009; Nightingale, 2009; Dankelman, 2010; MacGregor, 2010; Alston, 2011; Arora-Jonsson, 2011; Omolo, 2011; Resureccion, 2011).

Gender dimensions of vulnerability derive from differential access to the social and environmental resources required for adaptation. In many rural economies and resource-based livelihood systems, it is well established that women have poorer access than men to financial resources, land, education, health, and other basic rights. Further drivers of gender inequality stem from social exclusion from decision-making processes and labor markets, making women in particular less able to cope with and adapt to climate change impacts (Paavola, 2008; Djoudi and Brockhaus, 2011; Rijkers and Costa, 2012). These gender inequalities manifest themselves in gendered livelihood impacts and feminisation of responsibilities: whereas both men and women experience increases in productive roles, only women experience increased reproductive roles (Resureccion, 2011; Section 9.3.5.1.5, Box 13-1). A study in Australia, for example, showed how more regular occurrence of drought has put women under increasing pressure to earn off-farm income and contribute to more on-farm labor (Alston, 2011). Studies in Tanzania and Malawi demonstrate how women experience food and nutrition insecurity because food is preferentially distributed among other family members (Nelson and Stathers, 2009; Kakota et al., 2011).

AR4 assessed a body of literature that focused on women's relatively higher vulnerability to weather-related disasters in terms of number of deaths (Adger et al., 2007). Additional literature published since that time adds nuances by showing how socially constructed gender differences affect exposure to extreme events, leading to differential patterns of mortality for both men and women (*high confidence*; Section 11.3.3, Table 12-3). Statistical evidence of patterns of male and female mortality from recorded extreme events in 141 countries between 1981 and 2002 found that disasters kill women at an earlier age than men (Neumayer and Plümper, 2007; see also Box 13-1). Reasons for gendered differences in mortality include various socially and culturally determined gender roles. Studies in Bangladesh, for example, show that women do not learn to swim and so are vulnerable when exposed to flooding (Röhr, 2006) and that, in Nicaragua, the construction of gender roles means that middle-class women are expected to stay in the house,

even during floods and in risk-prone areas (Bradshaw, 2010). Although the differential vulnerability of women to extreme events has long been understood, there is now increasing evidence to show how gender roles for men can affect their vulnerability. In particular, men are often expected to be brave and heroic, and engage in risky life-saving behaviors that increase their likelihood of mortality (Box 13-1). In Hai Lang district, Vietnam, for example, more men died than women as a result of their involvement in search and rescue and protection of fields during flooding (Campbell et al., 2009). Women and girls are more likely to become victims of domestic violence after a disaster, particularly when they are living in emergency accommodation, which has been documented in the USA and Australia (Jenkins and Phillips, 2008; Anastario et al., 2009; Alston, 2011; Whittenbury, 2013; see also Box 13-1).

Heat stress exhibits gendered differences, reflecting both physiological and social factors (Section 11.3.3). The majority of studies in European countries show women to be more at risk, but their usually higher physiological vulnerability can be offset in some circumstances by relatively lower social vulnerability (if they are well connected in supportive social networks, for example). During the Paris heat wave, unmarried men were at greater risk than unmarried women, and in Chicago elderly men were at greatest risk, thought to reflect their lack of connectedness in social support networks which led to higher social vulnerability (Kovats and Hajat, 2008). A multi-city study showed geographical variations in the relationship between sex and mortality due to heat stress: in Mexico City, women had a higher risk of mortality than men, although the reverse was true in Santiago and São Paulo (Bell et al., 2008).

Recognizing gender differences in vulnerability and adaptation can enable gender-sensitive responses that reduce the vulnerability of women and men (Alston, 2013). Evaluations of adaptation investments demonstrate that those approaches that are not sensitive to gender dimensions and other drivers of social inequalities risk reinforcing existing vulnerabilities (Vincent et al., 2010; Arora-Jonsson, 2011; Figueiredo and Perkins, 2012). Government-supported interventions to improve production through cash-cropping and non-farm enterprises in rural economies, for example, typically advantage men over women because cash generation is seen as a male activity in rural areas (Gladwin et al., 2001; see also Section 13.3.1). In contrast, rainwater and conservation-based adaptation initiatives may require additional labor, which women cannot necessarily afford to provide (Baiphethi et al., 2008). Encouraging gender-equitable access to education and strengthening of social capital are among the best means of improving adaptation of rural women farmers (Goulden et al., 2009; Vincent et al., 2010; Below et al., 2012) and could be used to complement existing initiatives mentioned above that benefit men. Rights-based approaches to development can inform adaptation efforts as they focus on addressing the ways in which institutional practices shape access to resources and control over decision-making processes, including through the social construction of gender and its intersection with other factors that shape inequalities and vulnerabilities (Tschakert and Machado, 2012; Bee et al., 2013; Tschakert, 2013; see also Section 22.4.3 and Table 22-5).

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References

Adger, W.N., S. Agrawala, M.M.Q. Mirza, C. Conde, K. O'Brien, J. Pulhin, R. Pulwarty, B. Smit, and K. Takahashi, 2007: Chapter 17: Assessment of adaptation practices, options, constraints and capacity. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (ed.)]. IPCC, Geneva, Switzerland, pp. 719-743.

Alston, M., 2011: Gender and climate change in Australia. *Journal of Sociology*, **47**(**1**), 53-70.

Alston, M., 2013: Women and adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, (**4**)**5**, 351-358.

Anastario, M., N. Shebab, and L. Lawry, 2009: Increased gender-based violence among women internally displaced in Mississippi 2 years post-Hurricane Katrina. *Disaster Medicine and Public Health Preparedness*, **3**(**1**), 18-26.

Arora-Jonsson, S., 2011: Virtue and vulnerability: discourses on women, gender and climate change. *Global Environmental Change*, **21**, 744-751.

Baiphethi, M.N., M. Viljoen, and G. Kundhlande, 2008: Rural women and rainwater harvesting and conservation practices: anecdotal evidence from the Free State and Eastern Cape. *Agenda*, **22**(78), 163-171.

Bee, B., M. Biermann, and P. Tschakert, 2013: Gender, development, and rights-based approaches: lessons for climate change adaptation and adaptive social protection. In: *Research, Action and Policy: Addressing the Gendered Impacts of Climate Change* [Alston, M. and K. Whittenbury (eds.)]. Springer, Dordrecht, Netherlands, pp. 95-108.

Bell, M.L., M.S. O'Neill, N. Ranjit, V.H. Borja-Aburto, L.A. Cifuentes, and N.C. Gouveia, 2008: Vulnerability to heat-related mortality in Latin America: a case-crossover study in Sao Paulo, Brazil, Santiago, Chile and Mexico City, Mexico. *International Journal of Epidemiology*, **37**(**4**), 796-804.

Below, T.B., K.D. Mutabazi, D. Kirschke, C. Franke, S. Sieber, R. Siebert, and K. Tscherning, 2012: Can farmers' adaptation to climate change be explained by socio-economic household-level variables? *Global Environmental Change*, **22**(**1**), 223-235.

Bradshaw, S., 2010: Women, poverty, and disasters: exploring the links through Hurricane Mitch in Nicaragua. In: The International Handbook of Gender and Poverty: Concepts, Research, Policy [Chant, S. (ed.)]. Edward Elgar Publishing, Cheltenham, UK, pp. 627-632.

Brouwer, R., S. Akter, L. Brander, and E. Haque, 2007: Socioeconomic vulnerability and adaptation to environmental risk: a case study of climate change and flooding in Bangladesh. *Risk Analysis*, **27**(**2**), 313-326.

Campbell, B., S. Mitchell, and M. Blackett, 2009: *Responding to Climate Change in Vietnam. Opportunities for Improving Gender Equality*. A Policy Discussion Paper, Oxfam in Viet Nam and United Nations Development Programme-Viet Nam (UNDP-Viet Nam), Ha noi, Viet Nam, 62 pp.

Dankelman, I., 2010: Introduction: exploring gender, environment, and climate change. In: *Gender and Climate Change: An Introduction* [Dankelman, I. (ed.)]. Earthscan, London, UK and Washington, DC, USA, pp. 1-18.

Djoudi, H. and M. Brockhaus, 2011: Is adaptation to climate change gender neutral? Lessons from communities dependent on livestock and forests in northern Mali. *International Forestry Review*, **13**(**2**), 123-135.

Figueiredo, P. and P.E. Perkins, 2012: Women and water management in times of climate change: participatory and inclusive processes. *Journal of Cleaner Production*, **60**(**1**), 188-194.

Gladwin, C.H., A.M. Thomson, J.S. Peterson, and A.S. Anderson, 2001: Addressing food security in Africa via multiple livelihood strategies of women farmers. *Food Policy*, **26**(**2**), 177-207.

Goulden, M., L.O. Naess, K. Vincent, and W.N. Adger, 2009: Diversification, networks and traditional resource management as adaptations to climate extremes in rural Africa: opportunities and barriers. In: *Adapting to Climate Change: Thresholds, Values and Governance* [Adger, W.N., I. Lorenzoni, and K. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK, pp. 448-464.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)], Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp.

Jenkins, P. and B. Phillips, 2008: Battered women, catastrophe, and the context of safety after Hurricane Katrina. *NWSA Journal*, **20**(**3**), 49-68.

Kakota, T., D. Nyariki, D. Mkwambisi, and W. Kogi-Makau, 2011: Gender vulnerability to climate variability and household food insecurity. *Climate and Development*, **3**(**4**), 298-309.

Kovats, R. and S. Hajat, 2008: Heat stress and public health: a critical review. *Public Health*, **29**, 41-55.

MacGregor, S., 2010: 'Gender and climate change': from impacts to discourses. *Journal of the Indian Ocean Region*, **6**(**2**), 223-238.

Nelson, V. and T. Stathers, 2009: Resilience, power, culture, and climate: a case study from semi-arid Tanzania, and new research directions. *Gender & Development*, **17**(**1**), 81-94.

Neumayer, E. and T. Plümper, 2007: The gendered nature of natural disasters: the impact of catastrophic events on the gender gap in life expectancy, 1981-2002. *Annals of the Association of American Geographers*, **97**(**3**), 551-566.

Nightingale, A., 2009: Warming up the climate change debate: a challenge to policy based on adaptation. *Journal of Forest and Livelihood*, **8**(**1**), 84-89.

Omolo, N., 2011: Gender and climate change-induced conflict in pastoral communities: case study of Turkana in northwestern Kenya. *African Journal on Conflict Resolution*, **10**(**2**), 81-102.

Paavola, J., 2008: Livelihoods, vulnerability and adaptation to climate change in Morogoro, Tanzania. *Environmental Science & Policy*, **11**(**7**), 642-654.

Resurreccion, B.P., 2011: *The Gender and Climate Debate: More of the Same or New Pathways of Thinking and Doing?* Asia Security Initiative Policy Series, Working Paper No. 10, RSIS Centre for Non-Traditional Security (NTS) Studies, Singapore, 19 pp.

Rijkers, B. and R. Costa, 2012: *Gender and Rural Non-Farm Entrepreneurship*. Policy Research Working Paper 6066, Macroeconomics and Growth Team, Development Research Group, The World Bank, Washington, DC, USA, 68 pp.

Röhr, U., 2006: Gender and climate change. *Tiempo*, **59**, 3-7.

Tschakert, P., 2013: From impacts to embodied experiences: tracing political ecology in climate change research. *Geografisk Tidsskrift/Danish Journal of Geography*, 112(2), 144-158.

Tschakert, P. and M. Machado, 2012: Gender justice and rights in climate change adaptation: opportunities and pitfalls. *Ethics and Social Welfare*, **6**(**3**), 275-289, doi: 10.1080/17496535.2012.704929.

Vincent, K., T. Cull, and E. Archer, 2010: Gendered vulnerability to climate change in Limpopo province, South Africa. In: *Gender and Climate Change: An Introduction* [Dankelman, I. (ed.)]. Earthscan, London, UK and Washington, DC, USA, pp. 160-167.

Whittenbury, K., 2013: Climate change, women's health, wellbeing and experiences of gender-based violence in Australia. In: *Research, Action and Policy: Addressing the Gendered Impacts of Climate Change* [Alston, M. and K. Whittenbury (eds.)]. Springer Science, Dordrecht, Netherlands, pp. 207-222.

This cross-chapter box should be cited as:

K.E. Vincent, P. Tschakert, Barnett, J., M.G. Rivera-Ferre, and A. Woodward, 2014: Cross-chapter box on gender and climate change. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 105-107.

HS

Heat Stress and Heat Waves

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According to WGI, it is *very likely* that the number and intensity of hot days have increased markedly in the last three decades and *virtually certain* that this increase will continue into the late 21st century. In addition, it is *likely* (*medium confidence*) that the occurrence of heat waves (multiple days of hot weather in a row) has more than doubled in some locations, but *very likely* that there will be more frequent heat waves over most land areas after mid-century. Under a medium warming scenario, Coumou et al. (2013) predicted that the number of monthly heat records will be more than 12 times more common by the 2040s compared to a non-warming world. In a longer time perspective, if the global mean temperature increases to +7°C or more, the habitability of parts of the tropics and mid-latitudes will be at risk (Sherwood and Huber, 2010). Heat waves affect natural and human systems directly, often with severe losses of lives and assets as a result, and may act as triggers of tipping points (Hughes et al., 2013). Consequently, heat stress plays an important role in several key risks noted in Chapter 19 and CC-KR.

Economy and Society (Chapters 10, 11, 12, 13)

Environmental heat stress has already reduced the global labor capacity to 90% in peak months with a further predicted reduction to 80% in peak months by 2050. Under a high warming scenario (RCP8.5), labor capacity is expected to be less than 40% of present-day conditions in peak months by 2200 (Dunne et al., 2013). Adaptation costs for securing cooling capacities and emergency shelters during heat waves will be substantial.

Heat waves are associated with social predicaments such as increasing violence (Anderson, 2012) as well as overall health and psychological distress and low life satisfaction (Tawatsupa et al., 2012). Impacts are highly differential with disproportional burdens on poor people, elderly people, and those who are marginalized (Wilhelmi et al., 2012). Urban areas are expected to suffer more due to the combined effect of climate and the urban heat island effect (Fischer et al., 2012; see also Section 8.2.3.1). In low- and medium-income countries, adaptation to heat stress is severely restricted for most people in poverty and particularly those who are dependent on working outdoors in agriculture, fisheries, and construction. In small-scale agriculture, women and children are particularly at risk due to the gendered division of labor (Croppenstedt et al., 2013). The expected increase in wildfires as a result of heat waves (Pechony and Shindell, 2010) is a concern for human security, health, and ecosystems. Air pollution from wildfires already causes an estimated 339,000 premature deaths per year worldwide (Johnston et al., 2012).

Human Health (Chapter 11)

Morbidity and mortality due to heat stress is now common all over the world (Barriopedro et al., 2011; Nitschke et al., 2011; Rahmstorf and Coumou, 2011; Diboulo et al., 2012; Hansen et al., 2012). Elderly people and people with circulatory and respiratory diseases are also vulnerable even in developed countries; they can become victims even inside their own houses (Honda et al., 2011). People in physical work are at particular risk as such work produces substantial heat within the body, which cannot be released if the outside temperature and humidity is above certain limits (Kjellstrom et al., 2009). The risk of non-melanoma skin cancer from exposure to UV radiation during summer months increases with temperature (van der Leun, et al., 2008). High temperatures are also associated with an increase in air-borne allergens acting as triggers for respiratory illnesses such as asthma, allergic rhinitis, conjunctivitis, and dermatitis (Beggs, 2010).

Ecosystems (Chapters 4, 5, 6, 30)

Tree mortality is increasing globally (Williams et al., 2013) and can be linked to climate impacts, especially heat and drought (Reichstein et al., 2013), even though attribution to climate change is difficult owing to lack of time series and confounding factors. In the Mediterranean region, higher fire risk, longer fire season, and more frequent large, severe fires are expected as a result of increasing heat waves in combination with drought (Duguy et al., 2013; see also Box 4.2).

Marine ecosystem shifts attributed to climate change are often caused by temperature extremes rather than changes in the average (Pörtner and Knust, 2007). During heat exposure near biogeographical limits, even small (<0.5°C) shifts in temperature extremes can have large effects, often exacerbated by concomitant exposures to hypoxia and/or elevated CO_2 levels and associated acidification (*medium confidence*; Hoegh-Guldberg et al., 2007; see also Figure 6-5; Sections 6.3.1, 6.3.5, 30.4, 30.5; CC-MB).

Most coral reefs have experienced heat stress sufficient to cause frequent mass coral bleaching events in the last 30 years, sometimes followed by mass mortality (Baker et al., 2008). The interaction of acidification and warming exacerbates coral bleaching and mortality (*very high confidence*).Temperate seagrass and kelp ecosystems will decline with the increased frequency of heat waves and through the impact of invasive subtropical species (*high confidence*; Sections 5, 6, 30.4, 30.5, CC-CR, CC-MB).

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Agriculture (Chapter 7)

Excessive heat interacts with key physiological processes in crops. Negative yield impacts for all crops past +3°C of local warming without adaptation, even with benefits of higher CO_2 and rainfall, are expected even in cool environments (Teixeira et al., 2013). For tropical systems where moisture availability or extreme heat limits the length of the growing season, there is a high potential for a decline in the length of the growing season and suitability for crops (*medium evidence*, *medium agreement*; Jones and Thornton, 2009). For example, half of the wheat-growing area of the Indo-Gangetic Plains could become significantly heat-stressed by the 2050s.

There is *high confidence* that high temperatures reduce animal feeding and growth rates (Thornton et al., 2009). Heat stress reduces reproductive rates of livestock (Hansen, 2009), weakens their overall performance (Henry et al., 2012), and may cause mass mortality of animals in feedlots during heat waves (Polley et al., 2013). In the USA, current economic losses due to heat stress of livestock are estimated at several billion US$ annually (St-Pierre et al., 2003).

References

Anderson, C.A., 2012: Climate change and violence. In: *The Encyclopedia of Peace Psychology* [Christie, D.J. (ed.)]. John Wiley & Sons/Blackwell, Chichester, UK, pp. 128-132.

Baker, A.C., P.W. Glynn, and B. Riegl, 2008: Climate change and coral reef bleaching: an ecological assessment of long-term impacts, recovery trends and future outlook. *Estuarine, Coastal and Shelf Science*, **80**(**4**), 435-471.

Barriopedro, D., E.M. Fischer, J. Luterbacher, R.M. Trigo, and R. García-Herrera, 2011: The hot summer of 2010: redrawing the temperature record map of Europe. *Science*, **332**(**6026**), 220-224.

Beggs, P.J., 2010: Adaptation to impacts of climate change on aeroallergens and allergic respiratory diseases. *International Journal of Environmental Research and Public Health*, **7**(**8**), 3006-3021.

Coumou, D., A. Robinson, and S. Rahmstorf, 2013: Global increase in record-breaking monthly-mean temperatures. *Climatic Change*, **118**(**3-4**), 771-782.

Croppenstedt, A., M. Goldstein, and N. Rosas, 2013: Gender and agriculture: inefficiencies, segregation, and low productivity traps. *The World Bank Research Observer*, **28**(**1**), 79-109.

Diboulo, E., A. Sie, J. Rocklöv, L. Niamba, M. Ye, C. Bagagnan, and R. Sauerborn, 2012: Weather and mortality: a 10 year retrospective analysis of the Nouna Health and Demographic Surveillance System, Burkina Faso. *Global Health Action*, **5**, 19078, doi:10.3402/gha.v5i0.19078.

Duguy, B., S. Paula, J.G. Pausas, J.A. Alloza, T. Gimeno, and R.V. Vallejo, 2013: Effects of climate and extreme events on wildfire regime and their ecological impacts. In: *Regional Assessment of Climate Change in the Mediterranean, Volume 3: Case Studies* [Navarra, A. and L. Tubiana (eds.)]. Advances in Global Change Research Series: Vol. 52, Springer, Dordrecht, Netherlands, pp. 101-134.

Dunne, J.P., R.J. Stouffer, and J.G. John, 2013: Reductions in labour capacity from heat stress under climate warming. *Nature Climate Change*, **3**, 563-566.

Fischer, E., K. Oleson, and D. Lawrence, 2012: Contrasting urban and rural heat stress responses to climate change. *Geophysical Research Letters*, **39**(**3**), L03705, doi:10.1029/2011GL050576.

Hansen, J., M. Sato, and R. Ruedy, 2012: Perception of climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **109**(**37**), E2415-E2423.

Hansen, P.J., 2009: Effects of heat stress on mammalian reproduction. *Philosophical Transactions of the Royal Society B*, **364**(**1534**), 3341-3350.
Henry, B., R. Eckard, J.B. Gaughan, and R. Hegarty, 2012: Livestock production in a changing climate: adaptation and mitigation research in Australia. *Crop and Pasture Science*, **63**(**3**), 191-202.
Hoegh-Guldberg, O., P. Mumby, A. Hooten, R. Steneck, P. Greenfield, E. Gomez, C. Harvell, P. Sale, A. Edwards, and K. Caldeira, 2007: Coral reefs under rapid climate change and ocean acidification. *Science*, **318**(**5857**), 1737-1742.
Honda, Y., M. Ono, and K.L. Ebi, 2011: Adaptation to the heat-related health impact of climate change in Japan. In: *Climate Change Adaptation in Developed Nations: From Theory to Practice* [Ford, J.D. and L. Berrang-Ford (eds.)]. Springer, Dordrecht, Netherlands, pp. 189-203.
Hughes, T.P., S. Carpenter, J. Rockström, M. Scheffer, and B. Walker, 2013: Multiscale regime shifts and planetary boundaries. *Trends in Ecology & Evolution*, **28**(**7**), 389-395.
Johnston, F.H., S.B. Henderson, Y. Chen, J.T. Randerson, M. Marlier, R.S. DeFries, P. Kinney, D.M. Bowman, and M. Brauer, 2012: Estimated global mortality attributable to smoke from landscape fires. *Environmental Health Perspectives*, **120**(**5**), 695-701.
Jones, P.G. and P.K. Thornton, 2009: Croppers to livestock keepers: livelihood transitions to 2050 in Africa due to climate change. *Environmental Science & Policy*, **12**(**4**), 427-437.
Kjellstrom, T., R. Kovats, S. Lloyd, T. Holt, and R. Tol, 2009: The direct impact of climate change on regional labor productivity. *Archives of Environmental & Occupational Health*, **64**(**4**), 217-227.
Nitschke, M., G.R. Tucker, A.L. Hansen, S. Williams, Y. Zhang, and P. Bi, 2011: Impact of two recent extreme heat episodes on morbidity and mortality in Adelaide, South Australia: a case-series analysis. *Environmental Health*, **10**, 42, doi:10.1186/1476-069X-10-42.
Pechony, O. and D. Shindell, 2010: Driving forces of global wildfires over the past millennium and the forthcoming century. *Proceedings of the National Academy of Sciences of the United States of America*, **107**(**45**), 19167-19170.
Polley, H.W., D.D. Briske, J.A. Morgan, K. Wolter, D.W. Bailey, and J.R. Brown, 2013: Climate change and North American rangelands: trends, projections, and implications. *Rangeland Ecology & Management*, **66**(**5**), 493-511.
Pörtner, H.O. and R. Knust, 2007: Climate change affects marine fishes through the oxygen limitation of thermal tolerance. *Science*, **315**(**5808**), 95-97.
Rahmstorf, S. and D. Coumou, 2011: Increase of extreme events in a warming world. *Proceedings of the National Academy of Sciences of the United States of America*, **108**(**44**), 17905-17909.
Reichstein, M., M. Bahn, P. Ciais, D. Frank, M.D. Mahecha, S.I. Seneviratne, J. Zscheischler, C. Beer, N. Buchmann, and D.C. Frank, 2013: Climate extremes and the carbon cycle. *Nature*, **500**(**7462**), 287-295.
Sherwood, S.C. and M. Huber, 2010: An adaptability limit to climate change due to heat stress. *Proceedings of the National Academy of Sciences of the United States of America*, **107**(**21**), 9552-9555.
Smith, K.R., M. Jerrett, H.R. Anderson, R.T. Burnett, V. Stone, R. Derwent, R.W. Atkinson, A. Cohen, S.B. Shonkoff, and D. Krewski, 2010: Public health benefits of strategies to reduce greenhouse-gas emissions: health implications of short-lived greenhouse pollutants. *The Lancet*, **374**(**9707**), 2091-2103.
St-Pierre, N., B. Cobanov, and G. Schnitkey, 2003: Economic losses from heat stress by US livestock industries. *Journal of Dairy Science*, **86**, E52-E77.
Tawatsupa, B., V. Yiengprugsawan, T. Kjellstrom, and A. Sleigh, 2012: Heat stress, health and well-being: findings from a large national cohort of Thai adults. *BMJ Open*, **2**(**6**), e001396, doi:10.1136/bmjopen-2012-001396.
Teixeira, E.I., G. Fischer, H. van Velthuizen, C. Walter, and F. Ewert, 2013: Global hot-spots of heat stress on agricultural crops due to climate change. *Agricultural and Forest Meteorology*, **170**, 206-215.
Thornton, P., J. Van de Steeg, A. Notenbaert, and M. Herrero, 2009: The impacts of climate change on livestock and livestock systems in developing countries: a review of what we know and what we need to know. *Agricultural Systems*, **101**(**3**), 113-127.
van der Leun, J.C., R.D. Piacentini, and F.R. de Gruijl, 2008: Climate change and human skin cancer. *Photochemical & Photobiological Sciences*, **7**(**6**), 730-733.
Wilhelmi, O., A. de Sherbinin, and M. Hayden, 2012: Chapter 12. Exposure to heat stress in urban environments: current status and future prospects in a changing climate. In: *Ecologies and Politics of Health* [King, B. and K. Crews (eds.)]. Routledge Press, Abingdon, UK and New York, NY, USA, pp. 219-238.
Williams, A.P., C.D. Allen, A.K. Macalady, D. Griffin, C.A. Woodhouse, D.M. Meko, T.W. Swetnam, S.A. Rauscher, R. Seager, and H.D. Grissino-Mayer, 2013: Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change*, **3**, 292-297.

This cross-chapter box should be cited as:

Olsson, L., D.D. Chadee, O. Hoegh-Guldberg, M. Oppenheimer, J.R. Porter, H.-O. Pörtner, D. Satterthwaite, K.R. Smith, M.I. Travasso, and P. Tschakert, 2014: Cross-chapter box on heat stress and heat waves. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 109-111.

KR

A Selection of the Hazards, Key Vulnerabilities, Key Risks, and Emergent Risks Identified in the WGII Contribution to the Fifth Assessment Report

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The accompanying table provides a selection of the hazards, key vulnerabilities, key risks, and emergent risks identified in various chapters in this report (Chapters 4, 6, 7, 8, 9, 11, 13, 19, 22, 23, 24, 25, 26, 27, 28, 29, 30). Key risks are determined by hazards interacting with vulnerability and exposure of human systems, and ecosystems or species. The table underscores the complexity of risks determined by various climate-related hazards, non-climatic stressors, and multifaceted vulnerabilities. The examples show that underlying phenomena, such as poverty or insecure land-tenure arrangements, unsustainable and rapid urbanization, other demographic changes, failure in governance and inadequate governmental attention to risk reduction, and tolerance limits of species and ecosystems that often provide important services to vulnerable communities, generate the context in which climatic change related harm and loss can occur. The table illustrates that current global megatrends (e.g., urbanization and other demographic changes) in combination and in specific development context (e.g., in low-lying coastal zones), can generate new systemic risks in their interaction with climate hazards that exceed existing adaptation and risk management capacities, particularly in highly vulnerable regions, such as dense urban areas of low-lying deltas. A representative set of lines of sight is provided from across WGI and WGII. See Section 19.6.2.1 for a full description of the methods used to select these entries.

Table KR-1 | Examples of hazards/stressors, key vulnerabilities, key risks, and emergent risks.

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Terrestrial and Inland Water Systems (Chapter 4)	Rising air, soil, and water temperature (Sections 4.2.4, 4.3.2, 4.3.3)	Exceedance of eco-physiological climate tolerance limits of species (limited coping and adaptive capacities), increased viability of alien organisms	Risk of loss of native biodiversity, increase in non-native organism dominance	Cascades of native species loss due to interdependencies
		Health response to spread of temperature-sensitive vectors (insects)	Risk of novel and/or much more severe pest and pathogen outbreaks	Interactions among pests, drought, and fire can lead to new risks and large negative impacts on ecosystems.
	Change in seasonality of rain (Section 4.3.3)	Increasing susceptibility of plants and ecosystem services, due to mismatch between plant life strategy and growth opportunities	Changes in plant functional type mix leading to biome change with respective risks for ecosystems and ecosystem services	Fire-promoting grasses grow in winter-rainfall areas and provide fuel in dry summers.
Ocean Systems (Chapter 6)	Rising water temperature, increase of (thermal and haline) stratification, and marine acidification (Section 6.1.1)	Tolerance limits of endemic species surpassed (limited coping and adaptive capacities), increased abundance of invasive organisms, high susceptibility and sensitivity of warm water coral reefs and respective ecosystem services for coastal communities (Sections 6.3.1, 6.4.1)	Risk of loss of endemic species, mixing of ecosystem types, increased dominance of invasive organisms. Increasing risk of loss of coral cover and associated ecosystem with reduction of biodiversity and ecosystem services (Section 6.3.1)	Enhancement of risk as a result of interactions, e.g., acidification and warming on calcareous organisms (Section 6.3.5)
		New vulnerabilities can emerge as a result of shifted productivity zones and species distribution ranges, largely from low to high latitudes (Sections 6.3.4, 6.5.1), shifting fishery catch potential with species migration (Sections 6.3.1, 6.5.2, 6.5.3)	Risks due to unknown productivity and services of new ecosystem types (Sections 6.4.1, 6.5.3)	Enhancement of risk due to interactions of warming, hypoxia, acidification, new biotic interactions (Sections 6.3.5, 6.3.6)
	Expansion of oxygen minimum zones and coastal dead zones with stratification and eutrophication (Section 6.1.1)	Increasing susceptibility because hypoxia tolerance limits of larger animals surpassed, habitat contraction and loss for midwater fishes and benthic invertebrates (Section 6.3.3)	Risk of loss of larger animals and plants, shifts to hypoxia-adapted, largely microbial communities with reduced biodiversity (Section 6.3.3)	Enhancement of risk due to expanding hypoxia in warming and acidifying oceans (Section 6.3.5)
	Enhanced harmful algal blooms in coastal areas due to rising water temperature (Section 6.4.2.3)	Increasing susceptibility and limited adaptive capacities of important ecosystems and valuable services due to already existing multiple stresses (Sections 6.3.5, 6.4.1)	Increasing risk due to enhanced frequency of dinoflagellate blooms and respective potential losses and degradations of coastal ecosystems and ecosystem services (Section 6.4.2)	Disproportionate enhancement of risk due to interactions of various stresses (Section 6.3.5)
Food Security and Food Production Systems (Chapter 7)	Rising average temperatures and more frequent extreme temperatures (Sections 7.1, 7.2, 7.4, 7.5)	Susceptibility of all elements of the food system from production to consumption, particularly for key grain crops	Risk of crop failures, breakdown of food distribution and storage processes	Increase in the global population to about 9 billion combined with rising temperatures and other trace gases such as ozone affecting food production and quality. Upper temperature limit to the ability of some food systems to adapt
	Extreme precipitation and droughts (Section 7.4)	Crops, pasture, and husbandry are susceptible and sensitive to drought and extreme precipitation.	Risk of crop failure, risk of limited food access and quality	Flood and droughts affect crop yields and quality, and directly affect food access in most developing countries. (Section 7.4)
Urban Areas (Chapter 8)	Inland flooding (Sections 8.2.3, 8.2.4)	Large numbers of people exposed in urban areas to flood events. Particularly susceptible are people in low-income informal settlements with inadequate infrastructure (and often on flood plains or along river banks). These bring serious environmental health consequences from overwhelmed, aging, poorly maintained, and inadequate urban drainage infrastructure and widespread impermeable surfaces. Local governments are often unable or unwilling to give attention to needed flood-related disaster risk reduction. Much of the urban population unable to get or afford housing that protects against flooding, or insurance. Certain groups are more sensitive to ill health from flood impacts, which may include increased mosquito- and water-borne diseases.	Risks of deaths and injuries and disruptions to livelihoods/incomes, food supplies, and drinking water	In many urban areas, larger and more frequent flooding impacting much larger population. No insurance available or impacts reaching the limits of insurance. Shift in the burden of risk management from the state to those at risk, leading to greater inequality and property blight, abandonment of urban districts, and the creation of high-risk/high-poverty spatial traps
	Coastal flooding (including sea level rise and storm surge) (Sections 8.1.4, 8.2.3, 8.2.4)	High concentrations of people, businesses, and physical assets including critical infrastructure exposed in low-lying and unprotected coastal zones. Particularly susceptible is the urban population that is unable to get or afford housing that protects against flooding or insurance. The local government is unable or unwilling to give needed attention to disaster risk reduction.	Risks from deaths and injuries and disruptions to livelihoods/incomes, food supplies, and drinking water	Additional 2 billion or so urban dwellers expected over the next three decades Sea level rise means increasing risks over time, yet with high and often increasing concentrations of population and economic activities on the coasts. No insurance available or reaching the limits of insurance; shift in the burden of risk management from the state to those at risk leading to greater inequality and property blight, abandonment of urban districts, and the creation of high-risk/high-poverty spatial traps

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Urban Areas (continued) (Chapter 8)	Heat and cold (including urban heat island effect) (Section 8.2.3)	Particularly susceptible is a large and often increasing urban population of infants, young children, older age groups, expectant mothers, people with chronic diseases or compromised immune system in settlements exposed to higher temperatures (especially in heat islands) and unexpected cold spells. Inability of local organizations for health, emergency, and social services to adapt to new risk levels and set up needed initiatives for vulnerable groups	Risk of mortality and morbidity increasing, including shifts in seasonal patterns and concentrations due to hot days with higher or more prolonged high temperatures or unexpected cold spells. Avoiding risks often most difficult for low-income groups	Duration and variability of heat waves increasing risks over time for most locations owing to interactions with multiple stressors such as air pollution
	Water shortages and drought in urban regions (Sections 8.2.3, 8.2.4)	Lack of piped water to homes of hundreds of millions of urban dwellers. Many urban areas subject to water shortages and irregular supplies, with constraints on increasing supplies. Lack of capacity and resilience in water management regimes including rural–urban linkages. Dependence on water resources in energy production systems	Risks from constraints on urban water provision services to people and industry with human and economic impacts. Risk of damage and loss to urban ecology and its services including urban and peri-urban agriculture.	Cities' viability may be threatened by loss or depletion of freshwater sources—including for cities dependent on distant glacier melt water or on depleting groundwater resources.
	Changes in urban meteorological regimes lead to enhanced air pollution. (Section 8.2.3)	Increases in exposure and in pollution levels with impacts most serious among physiologically susceptible populations. Limited coping and adaptive capacities, due to lacking implementation of pollution control legislation of urban governments	Increasing risk of mortality and morbidity, lowered quality of life. These risks can also undermine the competitiveness of global cities to attract key workers and investment.	Complex and compounding health crises
	Geo-hydrological hazards (salt water intrusion, mud/land slides, subsidence) (Sections 8.2.3, 8.2.4)	Local structures and networked infrastructure (piped water, sanitation, drainage, communications, transport, electricity, gas) particularly susceptible. Inability of many low-income households to move to housing on safer sites.	Risk of damage to networked infrastructure. Risk of loss of human life and property	Potential for large local and aggregate impacts Knock-on effects for urban activities and well-being
	Wind storms with higher intensity (Sections 8.1.4, 8.2.4)	Substandard buildings and physical infrastructure and the services and functions they support particularly susceptible. Old and difficult to retrofit buildings and infrastructure in cities Local government unable or unwilling to give attention to disaster risk reduction (limited coping and adaptive capacities)	Risk of damage to dwellings, businesses, and public infrastructure. Risk of loss of function and services. Challenges to recovery, especially where insurance is absent	Challenges to individuals, businesses, and public agencies where the costs of retrofitting are high and other sectors or interests capture investment budgets; potential for tensions between development and risk reduction investments
	Changing hazard profile including novel hazards and new multi-hazard complexes (Sections 8.1.4, 8.2.4)	Newly exposed populations and infrastructure, especially those with limited capacity for multi-hazard risk forecasting and where risk reduction capacity is limited, e.g., where risk management planning is overly hazard specific including where physical infrastructure is predesigned in anticipation of other risks (e.g., geophysical rather than hydrometeorological)	Risks from failures within coupled systems, e.g., reliance of drainage systems on electric pumps, reliance of emergency services on roads and telecommunications. Potential of psychological shock from unanticipated risks	Loss of faith in risk management institutions. Potential for extreme impacts that are magnified by a lack of preparation and capacity in response
	Compound slow-onset hazards including rising temperatures and variability in temperature and water (Sections 8.2.2, 8.2.4)	Large sections of the urban population in low- and middle-income nations with livelihoods or food supplies dependent on urban and peri-urban agriculture are especially susceptible.	Risk of damage to or degradation of soils, water catchment capacity, fuel wood production, urban and peri-urban agriculture, and other productive or protective ecosystem services. Risk of knock-on impacts for urban and peri-urban livelihoods and urban health	Collapsing of peri-urban economies and ecosystem services with wider implications for urban food security, service provision, and disaster risk reduction
	Climate change–induced or intensified hazard of more diseases and exposure to disease vectors (Sections 8.2.3, 8.2.4)	Large urban population that is exposed to food-borne and water-borne diseases and to malaria, dengue, and other vector-borne diseases that are influenced by climate change	Risk due to increases in exposure to these diseases	Lack of capacity of public health system to simultaneously address these health risks with other climate-related risks such as flooding
Rural Areas (Chapter 9)	Drought in pastoral areas (Sections 9.3.3.1, 9.3.5.2)	Increasing vulnerability due to encroachment on pastoral rangelands, inappropriate land policy, misperception and undermining of pastoral livelihoods, conflict over natural resources, all driven by remoteness and lack of voice	Risk of famine Risk of loss of revenues from livestock trade	Increasing risks for rural livelihoods through animal disease in pastoral areas combined with direct impacts of drought
	Effects of climate change on artisanal fisheries (Sections 9.3.3.1, 9.3.5.2)	Artisanal fisheries affected by pollution and mangrove loss, competition from aquaculture, and the neglect of the sector by governments and researchers as well as complex property rights	Risk of economic losses for artisanal fisherfolk, due to declining catches and incomes and damage to fishing gear and infrastructure	Reduced dietary protein for those consuming artisanally caught fish, combined with other climate-related risks

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Rural Areas (continued) (Chapter 9)	Water shortages and drought in rural areas (Section 9.3.5.1.1)	Rural people lacking access to drinking and irrigation water. High dependence of rural people on natural resource-related activities. Lack of capacity and resilience in water management regimes (institutionally driven). Increased water demand from population pressure	Risk of reduced agricultural productivity of rural people, including those dependent on rainfed or irrigated agriculture, or high-yield varieties, forestry, and inland fisheries. Risk of food insecurity and decrease in incomes. Decreases in household nutritional status (Section 9.3.5.1)	Impacts on livelihoods driven by interaction with other factors (water management institutions, water demand, water used by non-food crops), including potential conflicts for access to water. Water-related diseases
Human Health (Chapter 11)	Increasing frequency and intensity of extreme heat	Older people living in cities are most susceptible to hot days and heat waves, as well as people with preexisting health conditions. (Section 11.3)	Risk of increased mortality and morbidity during hot days and heat waves. (Section 11.4.1) Risk of mortality, morbidity, and productivity loss, particularly among manual workers in hot climates	The number of elderly people is projected to triple from 2010 to 2050. This can result in overloading of health and emergency services.
	Increasing temperatures, increased variability in precipitation	Poorer populations are particularly susceptible to climate-induced reductions in local crop yields. Food insecurity may lead to undernutrition. Children are particularly vulnerable. (Section 11.3)	Risk of a larger burden of disease and increased food insecurity for particular population groups. Increasing risk that progress in reducing mortality and morbidity from undernutrition may slow or reverse. (Section 11.6.1)	Combined effects of climate impacts, population growth, plateauing productivity gains, land demand for livestock, biofuels, persistent inequality, and ongoing food insecurity for the poor
	Increasing temperatures, changing patterns of precipitation	Non-immune populations who are exposed to water- and vector-borne diseases that are sensitive to meteorological conditions (Section 11.3)	Increasing health risks due to changing spatial and temporal distribution of diseases strains public health systems, especially if this occurs in combination with economic downturn. (Section 11.5.1)	Rapid climate and other environmental change may promote emergence of new pathogens.
	Increased variability in precipitation	People exposed to diarrhea aggravated by higher temperatures, and unusually high or low precipitation (Section 11.3)	Risk that the progress to date in reducing childhood deaths from diarrheal disease is compromised (Section 11.5.2)	Increased rate of failure of water and sanitation infrastructure due to climate change leading to higher diarrhea risk
Livelihoods and Poverty (Chapter 13)	Increasing frequency and severity of droughts, coupled with decreasing rainfall and/or increased unpredictability of rainfall (Sections 13.2.1.2, 13.2.1.4, 13.2.2.2)	Poorly endowed farmers (high and persistent poverty), particularly in drylands, are susceptible to these hazards, since they have a very limited ability to compensate for losses in water-dependent farming systems and/or livestock.	Risk of irreversible harm due to short time for recovery between droughts, approaching tipping point in rainfed farming system and/or pastoralism	Deteriorating livelihoods stuck in poverty traps, heightened food insecurity, decreased land productivity, outmigration, and new urban poor in LICs and MICs
	Floods and flash floods in informal urban settlements and mountain environments, destroying physical assets (e.g., homes, roads, terraces, irrigation canals) (Sections 13.2.1.1, 13.2.1.3, 13.2.1.4)	High exposure and susceptibility of people, particularly children and elderly, as well as disabled in flood-prone areas. Inadequate infrastructure, culturally imposed gender roles, and limited ability to cope and adapt due to political and institutional marginalization and high poverty adds to the susceptibility of these people in informal urban settlements; limited political interest in development and building adaptive capacity	Risk of high morbidity and mortality due to floods and flash floods. Factors that further increase risk may include a shift from transient to chronic poverty due to eroded human and economic assets (e.g., labor market) and economic losses due to infrastructure damage.	Exacerbated inequality between better-endowed households able to invest in flood-control measures and/or insurance and increasingly vulnerable populations prone to eviction, erosion of livelihoods, and outmigration
	Increased variability of precipitation; shifts in mean climate and extreme events (Sections 13.2.1.1, 13.2.1.4)	Limited ability to cope owing to exhaustion of social networks, especially among the elderly and female-headed households; mobilization of labor and food no longer possible	Hazard combines with vulnerability to shift populations from transient to chronic poverty due to persistent and irreversible socioeconomic and political marginalization. In addition, the lack of governmental support, as well as limited effectiveness of response options, increase the risk.	Increasing yet invisible multidimensional vulnerability and deprivation at the convergence of climatic hazards and socioeconomic stressors
	Successive and extreme events (floods, droughts) coupled with increasing temperatures and rising water demand (Sections 13.2.1.1, 13.2.1.5)	Rural communities are particularly susceptible, due to the marginalization of rural water users to the benefit of urban users, given political and economic priorities (e.g., Australia, Andes, Himalayas, Caribbean).	Risk of loss of rural livelihoods, severe economic losses in agriculture, and damage to cultural values and identity; mental health impacts (including increased rates of suicide)	Loss of rural livelihoods that have existed for generations, heightened outmigration to urban areas; emergence of new poverty in MICs and HICs
	Sea level rise (Sections 13.1.4, 13.2.1.1, 13.2.2.1, 13.2.2.3)	High number of people exposed in low-lying areas coupled with high susceptibility due to multidimensional poverty, limited alternative livelihood options among poor households, and exclusion from institutional decision-making structures	Risk of severe harm and loss of livelihoods. Potential loss of common-pool resources; of sense of place, belonging, and identity, especially among indigenous populations	Loss of livelihoods and mental health risks due to radical change in landscape, disappearance of natural resources, and potential relocation; increased migration
	Increasing temperatures and heat waves (Sections 13.2.1.5, 13.2.2.3, 13.2.2.4)	Agricultural wage laborers, small-scale farmers in areas with multidimensional poverty and economic marginalization, children in urban slums, and the elderly are particularly susceptible.	Risk of increased morbidity and mortality due to heat stress, among male and female workers, children, and the elderly, limited protection due to socioeconomic discrimination and inadequate governmental responses	Declining labor pool for agriculture coupled with new challenges for rural health care systems in LICs and MICs; aging and low-income populations without safety nets in HICs at risk

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Livelihoods and Poverty (continued) (Chapter 13)	Increased variability of rainfall and/or extreme events (floods, droughts, heat waves) (Sections 13.2.1.1, 13.2.1.3, 13.2.1.4, 13.2.1.5)	People highly dependent on rainfed agriculture are particularly at risk. Persistent poverty among subsistence farmers and urban wage laborers who are net buyers of food with limited coping mechanisms	Risk of crop failure, spikes in food prices, reduction in consumption to protect household assets, risk of food insecurity, shifts from transient to chronic poverty due to limited ability to reduce risks	Food riots, child food poverty, global food crises, limits of insurance and other risk-spreading strategies
	Changing rainfall patterns (temporally and spatially)	Households or people with a high dependence on rainfed agriculture and little access to alternative modes of income	Risks of crop failure, food shortage, severe famine	Coincidence of hazard with periods of high global food prices leads to risk of failure of coping strategies and adaptation mechanisms such as crop insurance (risk spreading).
	Stressor from soaring demand (and prices) for biofuel feedstocks due to climate policies	Farmers and groups that have unclear and/or insecure land tenure arrangements are exposed to the dispossession of land due to land grabbing in developing countries.	Risk of harm and loss of livelihoods for some rural residents due to soaring demand for biofuel feedstocks and insecure land tenure and land grabbing	Creation of large groups of landless farmers unable to support themselves. Social unrest due to disparities between intensive energy production and neglected food production
	Increasing frequency of extreme events (droughts, floods), e.g., if 1:20 year drought/flood becomes 1:5 year drought/flood	Pastoralists and small farmers subject to damage to their productive assets (e.g., herds of livestock; dykes, fences, terraces)	Risk of the loss of livelihoods and harm due to shorter time for recovery between extremes. Pastoralists restocking after a drought may take several years; in terraced agriculture, need to rebuild terraces after flood, which may take several years	Collapse of coping strategies with risk of collapsing livelihoods. Adaptation mechanisms such as insurance fail due to increasing frequency of claims.
Emergent Risks and Key Vulnerabilities (Chapter 19)	Warming and drying (precipitation changes of uncertain magnitude) (WGI AR5 TS 5.3; SPM; Sections 11.3, 12.4)	Limits to coping capacity to deal with reduced water availability; increasing exposure and demand due to population increase; conflicting demands for alternative water uses; sociocultural constraints on some adaptation options (Sections 19.2.2, 19.3.2.2, 19.6.1.1, 19.6.3.4)	Risk of harm and loss due to livelihood degradation from systematic constraints on water resource use that lead to supply falling far below demand. In addition, limited coping and adaptation options increase the risk of harm and loss. (Sections 19.3.2.2, 19.6.3.4)	Competition for water from diverse sectors (e.g., energy, agriculture, industry) interacts with climate changes to produce locally severe shortages. (Sections 19.3.2.2, 19.6.3.4)
	Changes in regional and seasonal temperature and precipitation over land (WGI AR5 TS 5.3; SPM; Sections 11.3, 12.4)	Communities highly dependent on ecosystem services (Sections 19.2.2.1, 19.3.2.1) which are negatively affected by changes in regional and seasonal temperature	Risk of large-scale species richness loss over most of the global land surface. 57 ± 6% of widespread and common plants and 34 ± 7% of widespread and common animals are expected to lose ≥50% of their current climatic range by the 2080s leading to loss of services. (Section 19.3.2.1)	Widespread loss of ecosystem services, including: provisioning, such as food and water; regulating, such as the control of climate and disease; supporting, such as nutrient cycles and crop pollination; and cultural, such as spiritual and recreational benefit (Sections 19.3.2.1, 19.6.3.4)
Africa (Chapter 22)	Increasing temperature	Children, pregnant women, and those with compromised health status are particularly at risk for temperature-related changes in diarrheal and vector-borne diseases, and for temperature-related reductions in crop yields. Outdoor workers, older adults, and young children are most susceptible to hot weather and heat waves. (Sections 22.3.5.2, 22.3.5.4)	Risk of changes in the geographic distribution, seasonality, and incidence of infectious diseases, leading to increases in the health burden. Risk of increased burdens of stunting in children. Risk of increase in morbidity and mortality during hot days and heat waves	Interactions among factors lead to emerging and re-emerging epidemics.
		Populations dependent on aquatic systems and aquatic ecosystem services that are sensitive to increased water temperatures	Loss of aquatic ecosystems and risks for people who might depend on these resources; reduction in freshwater fisheries production (Sections 22.3.2.2, 22.3.4.4)	Risk of loss of livelihoods due to interactions of loss of ecosystem services and other climate-related stressors on poor communities
		Rural and urban populations whose food and livelihood security is diminished	Risk of harm and loss due to increased heat stress on crops and livestock resulting in reduced productivity; increased food storage losses due to spoilage (Sections 22.3.4.1, 22.3.4.2)	Range expansion of crop pests and diseases to high-elevation agroecosystems (Section 22.3.4.3)
	Extreme events, e.g., floods and flash floods (and drought)	Population groups living in informal settlements in highly exposed urban areas; women and children often the most vulnerable to disaster risk (Sections 22.3.6, 22.4.3)	Increasing risk of mortality, harm and losses due to water logging triggered by heavy rainfall events	Compounded risk of epidemics including diarrheal diseases (e.g., cholera)
		Susceptible groups include those who experience diminished access to food resulting from reduced capacity to transport, store, and market food, such as the urban poor.	Risk of food shortages and of damages to the food system due to storms and flooding	Food price spikes due to convergence of climatic and non-climatic forces that reduce food access for the poor whose income is disproportionately spent on food (Section 22.3.4.5)
		Children, pregnant women, and those with compromised health status are particularly vulnerable to reduced access to safe water and improved sanitation and increasing food insecurity. (Sections 22.3.5.2, 22.3.5.3)	Risk of crop and livestock losses from drought Risk of reduced water supply and quality for household use. (Sections 22.3.4.1, 22.3.4.2) Risk of increased incidence of food- and water-borne diseases (e.g., cholera) and undernutrition. Risk of drinking water contamination due to heavy precipitation events and flooding (Section 22.3.5.2)	Compound effects of high temperature and changes in rainfall on human and natural systems. Increased incidence of stunting in children (Section 22.3.5.3)

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Europe (Chapter 23)	Extreme weather events (Section 23.9)	Sectors with limited coping and adaptive capacity as well as high sensitivity to these extreme events, such as transport, energy, and health, are particularly susceptible.	Risk of new systemic threats due to stress on multiple and interconnected sectors. Risk of failure of service provision of one or more sectors	Disproportionate intensification of risk due to increasing interdependencies
	Climate change increases the spatial distribution and seasonality of pests and diseases. (Section 23.4.1, 23.4.3, 23.4.4)	High susceptibility of plants and animals that are exposed to pests and diseases	Risk of increases in crop losses and animal diseases or even fatalities of livestock	Increasing risks due to limited response options and various feedback processes in agriculture, e.g., use of pesticides or antibiotics to protect plants and livestock increases resistance of disease vectors
	Extreme weather events and reduced water availability due to climate change (Section 23.3.4)	Low adaptive capacity of power systems might lead to limited energy supply as well as higher supply costs during such extreme events and conditions.	Increasing risk of power shortages due to limited energy supply, e.g., of nuclear power plants due to limited cooling water during heat stress	Continued underinvestment in adaptive energy systems might increase the risk of mismatches between limited energy supply during these events and increased demands, e.g., during a heat wave.
Asia (Chapter 24)	Rising average temperatures and more frequent extreme temperatures, as well as changing rainfall patterns (temporally and spatially)	Food systems and food production systems for key grain crops, particularly rice and other cereal crop farming systems, are highly susceptible. (Section 24.4.4.3)	Risk of crop failures and lower crop yield also can increase the risk of major losses for farmers and rural livelihoods. (Section 24.4.4.3)	Increase in Asian population combined with rising temperatures affecting food production. Upper temperature limit to the ability of some food systems to adapt could be reached.
	Rising sea level	Paddy fields and farmers near the coasts are particularly susceptible. (Section 24.4.4.3)	Risk of loss of arable areas due to submergence (Section 24.4.4.3)	Migration of farming communities to higher elevation areas entails risks for migrants and receiving regions.
	Projected increase in frequency of various extreme events (heat wave, floods, and droughts) and sea level rise	Increasing exposure due to convergence of livelihood and properties into coastal megacities. People in areas that are not sufficiently protected against natural hazards are particularly susceptible.	Risk of loss of life and assets due to coastal floods accompanied by increasing vulnerabilities.	Projected increase in disruptions of basic services such as water supply, sanitation, energy provision, and transportation systems, which themselves could increase vulnerabilities
Australasia (Chapter 25)	Rising air and sea surface temperatures, drying trends, reduced snow cover, increased intensity of severe cyclones, ocean acidification (Section 25.2; Table 25-1; Figure 25-4; WGI AR5 Chapter 14 and Atlas)	Species that live in a limited climatic range and that suffer from habitat fragmentation as well as from external stressors (pollution, runoff, fishing, tourism, introduced predators, and pests) are especially susceptible. (Sections 25.6.1, 25.6.2)	Risk of significant change in community composition and structure of coral reefs and montane ecosystems and risk of loss of some native species in Australia (Sections 25.6.1, 25.6.2, 25.10.2)	Increasing risk from compound extreme events across time and space, and cumulative adaptation needs, with recovery and risk reduction measures hampered further by impacts and responses reaching across different levels of government (Sections 25.10.2, 25.10.3; Box 25-9)
	Increased extreme rainfall related to flood risk in many locations (Section 25.2; Table 25-1)	Adaptation deficit of existing infrastructure and settlements to current flood risk; expansion and densification of urban areas; effective adaptation includes transformative changes such as land-use controls and retreat. (Sections 25.3, 25.10.2; Box 25-8)	Increased frequency and intensity of flood damage to infrastructure and settlements in Australia and New Zealand (Box 25-8; Section 25.10.2)	
	Continuing sea level rise, with projections spanning a particularly large range and continuing beyond 2100, even under mitigation scenarios (Section 25.2; Box 25-1; WGI AR5 Chapter 13)	Long-lived and high asset value coastal infrastructure and low-lying ecosystems are highly susceptible. Expansion of coastal populations and assets into coastal zones increases the exposure. Conflicting priorities constrain adaptation options and limit effective response strategies. (25.3, Box 25-1)	Increasing risks to coastal infrastructure and low-lying ecosystems in Australia and New Zealand, with widespread damages toward the upper end of projected ranges (Box 25-1; Sections 25.6.1, 25.6.2, 25.10.2)	
North America (Chapter 26)	Increases in frequency and/or intensity of extreme events, such as heavy precipitation, river and coastal floods, heat waves, and droughts (Sections 26.2.2, 26.3.1, 26.8.1)	Physical infrastructure in a declining state in urban areas particularly susceptible. Also increases in income disparities and limited institutional capacities might result in larger proportions of people susceptible to these stressors due to limited economic resources. (Sections 26.7, 26.8.2)	Risk of harm and loss in urban areas, particularly in coastal and dry environments due to enhanced vulnerabilities of social groups, physical systems, and institutional settings combined with the increases of extreme weather events (Section 26.8.1)	Inability to reduce vulnerability in many areas results in an increase in risk more so than change in physical hazard. (Section 26.8.3)
	Higher temperatures, decreases in runoff, and lower soil moisture due to climate change (Sections 26.2, 26.3)	Vulnerability of small rural landholders, particularly in Mexican agriculture, and of the poor in rural settlements (Sections 26.5, 26.8.2.2)	Risk of increased losses and decreases in agricultural production. Risk of food and job insecurity for small landholders and social groups in regions exposed to these phenomena (Sections 26.5, 26.8.2.2)	Increasing risks of social instability and local economic disruption due to internal migration (Sections 26.2.1, 26.8.3)

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
North America (continued) (Chapter 26)	Wildfires and drought conditions (Box 26-2)	Indigenous groups, low-income residents in peri-urban areas, and forest systems (Box 26-2; Section 26.8.2)	Risk of loss of ecosystem integrity, property loss, human morbidity, and mortality due to wildfires (Box 26-2; Section 26.8.3)	
	Extreme storm and heat events, air pollution, pollen, and infectious diseases (Section 26.6.1)	Susceptibility of individuals is determined by factors such as economic status, preexisting illness, age, and access to assets. (Section 26.6.1)	Increasing risk of extreme temperature-, storm-, pollen-, and infectious diseases–related human morbidity or mortality (Section 26.6.2)	
	River and coastal floods, and sea level rise (Sections 26.2.2, 26.4.2, 26.8.1)	Increasing exposure of populations, property, as well as ecosystems, partly resulting from overwhelmed drainage networks. Groups and economic sectors that highly depend on the functioning of different supply chains, public health institutions that can be disrupted, and groups that have limited coping capacities to deal with supply chain interruptions and disruptions to their livelihoods are particularly susceptible. (Sections 26.7, 26.8.1)	Risk of property damage, supply chain disruption, public health, water quality impairment, ecosystem disruption, infrastructure damage, and social system disruption from urban flooding due to river and coastal floods and floods of drainage networks (Sections 26.4.2, 26.8.1)	Multiple risks from interacting hazards on populations' livelihoods, infrastructure, and services (Sections 26.7, 26.8.3)
Central and South America (Chapter 27)	Reduced water availability in semi-arid regions and regions dependent on glacier meltwater; flooding in urban areas due to extreme precipitation (Sections 27.2.1, 27.3.3)	Groups that cannot keep agricultural livelihoods and are forced to migrate are especially vulnerable. Limited infrastructure and planning capacity can further increase the lack of coping and adaptive capacities to rapid changes expected (precipitation), especially in large cities.	Risk of loss of human lives, livelihood, and property	Increase in infectious diseases. Economic impacts due to reallocation of populations
	Ocean acidification and warming (Section 27.3.3; Box CC-OA)	Sensitivity of coral reef systems to ocean acidification and warming	Risk of loss of biodiversity (species) and risk of a reduced fishing capacity with respective impacts for coastal livelihoods	Economic losses and impact on food (fishery) production in certain regions
	Extremes of drought/ precipitation (Sections 27.2.1, 27.3.4)	Elevated CO_2 decreases nutrient contents in plants, especially nitrogen in relation to carbon in food products.	Risk of loss of (food) production and productivity in some regions where extreme events may occur. Need to adjust diet due to decrease in food quality (e.g., less protein due to lower nitrogen assimilation). Decrease in bioenergy production	Strong economic impacts related to the need to move crops to more suitable regions. Teleconnections (related to food quality) related to the intense exportation of food by the region. Impacts on energy system and carbon emissions with consequent increase in fossil fuel demand.
	Higher temperatures and humidity lead to a spread of vector-borne diseases in altitude and latitude. (Section 27.3.7)	People exposed and vulnerable to vector-borne diseases and an increase in mosquito biting rates that increase the probability of human infections	Risk of increase in morbidity and in disability-adjusted life years (DALYs); risk of loss of human lives; risk of decrease in school and labor productivity	High economic impacts owing to the necessity to increase the financing of health programs, as well as the costs of DALYs, increase in hospitals and medical infrastructure adequate to cope with increasing disease incidence rates, and the spread of diseases to newer regions
Polar Regions (Chapter 28)	Loss of multi-year ice and reductions in the spatial extent of summer sea ice (Sections 28.2.5, 28.3.2, 28.4.1)	Indigenous communities that depend on sea ice for traditional livelihoods are vulnerable to this hazard, particularly due to loss of breeding and foraging platforms for marine mammals.	Risk of loss of traditional livelihoods and food sources.	Top-down shifts in food webs
		Ecosystems are vulnerable owing to the shifts in the distribution and timing of ice algal and ocean phytoplankton blooms.	Risk of disruption of synchronized timing of zooplankton ontogeny and availability of prey. Increased variability in secondary production while zooplankton adapt to shifts in timing. Risks also to local marine food webs.	Bottom up shifts in food webs. Potential changes in pelagic and benthic coupling
	Ocean acidification (Sections 28.2.2, 28.3.2)	Tolerance limits of endemic species surpassed. Impacts on exoskeleton formation for some species and alteration of physiological and behavioral properties during larval development	Localized loss of endemic species, local impacts on marine food webs	Localized declines in commercial fisheries. Local declines in fish, shellfish, seabirds, and marine mammals
	Shifts in boundaries of marine eco-regions due to rising water temperature, shifts in mixed layer depth, changes in the distribution and intensity of ocean currents (Sections 28.2.2, 28.3.2)	Marine organisms that are susceptible to spatial shifts are particularly vulnerable.	Risk of changes in the structure and function of marine systems and potentially species invasions	Disputes over international fisheries and shared stocks

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Polar Regions (continued) (Chapter 28)	Declining sea ice, changes in snow and ice timing and state, decreasing predictability of weather (Sections 28.1, 28.4.1)	Many traditional subsistence food sources—especially for indigenous peoples—such as Arctic marine and land mammals, fish, and waterfowl. Various traditional livelihoods are susceptible to these hazards.	Risk of loss of habitats and changes in migration patterns of marine species	Enhancement of risk to food security and basic nutrition—especially for indigenous peoples—from loss of subsistence foods and increased risk to subsistence hunters', herders', and fishers' health and safety in changing ice conditions
	Increased river and coastal flooding and erosion and thawing of permafrost (Sections 28.2.4, 28.3.1, 28.3.4)	Rural and remote communities as well as urban communities in low-lying Arctic areas are exposed. Susceptibility and limited coping capacity of community water supplies due to potential damages to infrastructure.	Community and public health infrastructure damaged resulting in disease from contamination and sea water intrusion	Reduced water quality and quantity may result in increased rates of infection, other medical problems, and hospitalizations.
	Extreme and rapidly changing weather, intense weather and precipitation events, rapid snow and ice melt, changing river and sea ice conditions, permafrost thaw (Section 28.2.4)	People living from subsistence travel and hunting, herding, and fishing, for example indigenous peoples in remote and isolated communities, are particularly susceptible.	Accidents, physical/mental injuries, death, and cold-related exposure, injuries, and diseases	Enhanced risks to safe travel or subsistence hunting, herding, fishing activities affect livelihoods and well-being.
	Diminished sea ice; earlier sea ice melt-out; faster sea ice retreat; thinner, less predictable ice in general; greater variability in snow melt/freeze; ice, weather, winds, temperatures, precipitation (Sections 28.2.5, 28.2.6, 28.4.1)	Livelihoods of many indigenous peoples (e.g., Inuit and Saami) depend upon subsistence hunting and access to and favorable conditions for animals. These livelihoods are susceptible. Also marine ecosystems are susceptible (e.g., marine mammals).	Risk of loss of livelihoods and damage due to, e.g., more difficult access to marine mammals associated with diminishing sea ice (a risk to the Inuit), and loss of access by reindeer to their forage under snow due to ice layers formed by warming winter temperatures and "rain on snow" (a risk to the Saami).	Enhanced risk of loss of livelihoods and culture of increasing numbers of indigenous peoples, exacerbated by increasing loss of lands and sea ice for hunting, herding, fishing due to enhanced petroleum and mineral exploration, and increased maritime traffic
Small Islands (Chapter 29)	Increases in intensity of tropical cyclones (WGI AR5 Sections 14.6, 14.8.4)	Various countries and communities are vulnerable to these hazards because of their high dependence on natural and ecological systems for security of settlements and tourism (Section 29.3.3.1), human health (Section 29.3.3.2), and water resources (Section 29.3.2).	Risk of loss of ecosystems, settlements, and infrastructure, as well as negative impacts on human health and island economies (Figure 29-4)	Increased risk of interactions of damages to ecosystems, settlements, island economies, and risks to human life (Section 29.6; Figure 29-4)
	Ocean warming and acidification leading to coral bleaching (Sections 29.3.1.2, 30.5.4.2, 30.5.6.1.1, 30.5.6.2)	Tropical island communities are highly dependent on coral reef ecosystems for subsistence life styles, food security, coastal protection and beach, and reef-based tourist economic activity, and hence are highly susceptible to the hazard of coral bleaching. (Sections 29.3.1.2, 30.6.2.1.2)	Risk of decline and possible loss of coral reef ecosystems through thermal stress. Risk of serious harm and loss of subsistence lifestyles. Risk of loss of coastal protection and beaches, risk of loss of tourist revenue (Sections 29.3.1.1, 29.3.1.2)	Impacts on human health and loss of subsistence lifestyles. Potential increase in internal migration/urbanization (Section 29.3.3.3; Chapter 9)
	Sea level rise (Sections 29.3.1.1, 30.3.1.2; WGI AR5 Section 3.7.1)	Many small island communities and associated settlements and infrastructure are in low-lying coastal zones (high exposure) and are also vulnerable to increasing inundation, erosion and wave incursion. (Sections 5.3.2, 29.3.1.1; Figure 29-2)	Risk of loss and harm due to sea level rise in small island communities. Global mean sea level is likely to increase by 0.35 to 0.70 m for Representative Concentration Pathway (RCP) 4.5 during the 21st century, threatening low-lying coastal areas and atoll islands. (Section 29.4.3, Table 29-1; WGI AR5 Section 13.5.1, Table 13.5)	Incremental upwards shift in sea-level baselines results in increased frequency and extent of marine flooding during high tides and episodic storm surges. These events could render soils and fresh groundwater resources unfit for human use before permanent inundation of low-lying areas. (Sections 29.3.1.1, 29.3.2, 29.3.3.1, 29.5.1)

Continued next page →

Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
The Ocean (Chapter 30)	Increasing ocean temperatures. Increased frequency of thermal extremes	Corals and other organisms whose tolerance limits are exceeded are particularly susceptible (especially CBS, STG, SES, and EUS ocean regions). (Sections 6.2.2.1, 6.2.2.2, 30.5.2, 30.5.4, 30.5.5; Boxes CC-CR, 30.5.6, CC-OA)	Risk of increased mass coral bleaching and mortality (loss of coral cover) with severe risks for coastal fisheries, tourism, and coastal protection (Sections 6.3.2. 6.3.5, 5.4.2.4, 7.2.1.2, 6.4.1.4, 29.3.1.2, 30.5.2, 30.5.3, 30.5.4, 30.5.5; Box CC-CR)	Loss of coastal reef systems, risk of decreased food security and reduced livelihoods, and reduced coastal protection (Sections 7.2.1.2, 30.6.2.1, 30.6.5)
		Marine species and ecosystems as well as fisheries and coastal livelihoods and tourism that cannot cope or adapt to changing temperatures and changes in the distribution are particularly vulnerable, especially for HLSBS, CBS, STG, and EBUE. (Sections 6.3.2, 6.3.4, 7.3.2.6, 30.5; Box CC-BIO)	Risk for fishery and coastal livelihoods. Fishery opportunity changes as stock abundance may rise or fall; increased risk of disease and invading species impacting ecosystems and fisheries (Sections 6.3.5, 6.4.1.1, 6.5.3, 7.3.2.6, 7.4.2, 29.5.3, 29.5.4)	Significant risk of fishery collapse may develop as the capacity of fisheries to resist the following is exceeded: a) fundamental change to fishery composition, and b) the increased migration of disease and other organisms. (Sections 6.5.3, 7.5.1.1.3)
		Coastal ecosystems and communities that might be exposed to phenomena of elevated rates of microbial respiration leading to reduced oxygen at depth and increased spread of dead zones are particularly vulnerable (particularly for EBUE, SES, EUS).	Risk of loss of habitats and fishery resources as well as losses of key fisheries species. Oxygen levels decrease, leading to impacts on ecosystems (e.g., loss of habitat) and organisms (e.g., physiological performance of fish) resulting in reduced capture of key fisheries species.	Increasing risk of loss of livelihoods
		Deep sea life is sensitive to hazards and to change given the very constant conditions under which it has evolved. (30.1.3.1.3, 30.5.2, 30.5.5)	Risk of fundamental changes in conditions associated with deep sea (e.g., oxygen, pH, carbonate, CO_2, temperature) drive fundamental changes that result in broad-scale changes throughout the ocean. (Sections 30.1.3.1.3, 30.5.2, 30.5.5; Boxes CC-UP, CC-NPP)	Changes in the deep ocean may be a prelude to ocean wide changes with planetary implications.
	Rising ocean acidification	Reef systems, corals, and coastal ecosystems that are exposed to a reduced rate of calcification and greater decalcification leading to potential loss of carbonate reef systems, corals, molluscs, and other calcifiers in key regions, such as the CBS, STG (Section 6.2.2.2)	Risk of the alteration of ecosystem services including risks to food provisioning with impacts on fisheries and aquaculture (Sections 6.2.5.3, 7.2.1.2, 7.3.2, 7.4.2,)	Income and livelihoods for communities are reduced as productivity of fisheries and aquaculture diminish. (Sections 7.5.1.1.3, 30.6)
		Marine organisms that are susceptible to changes in pH and carbonate chemistry imply a large number of changes to the physiology and ecology of marine organisms (particularly in CBS, STG, SES regions). (Sections 6.2.5, 6.3.4, 30.3.2.2)	Risk of fundamental shifts in ecosystems composition as well as organism function occur, leading to broad scale and fundamental change. Income and livelihoods from dependent communities are affected as ecosystem goods and services decline, with the prospect that recovery may take tens of thousands of years. (Section 6.1.1.2)	Risk to ecosystems and livelihoods is increased by the potential for interaction among ocean warming and acidification to create unknown impacts. (Section CC-OA)
		Coastal systems are increasingly exposed to upwelling in some areas, which results in periods of high CO_2, low O_2 and pH. (Box CC-UP; Sections 6.2.2.2, 6.2.5.3)	Risk of loss and harm to fishery and aquaculture operations and respective livelihoods (e.g., oyster cultivation), especially those exposed periodically to harmful conditions during elevated upwelling, which trigger adaptation responses. (Section 30.6.2.1.4)	Background pH and carbonate chemistry are also such that harmful conditions are always present (avoiding impacts via adaptation not possible any more). (Section 30.6.2.1.4)
	Increased stratification as a result of ocean warming; reduced ventilation	Ocean ecosystems are vulnerable due to the reduced regeneration of nutrients as mixing between the ocean and its surface is reduced (EUS, STG, and EBUE). (Sections 6.2, 6.3, 6.5, 30.5.2, 30.5.4, 30.5.5)	Risk of productivity losses of oceans and respective negative impacts on fisheries. The concentration of inorganic nutrients in the upper layers of the ocean is reduced, leading to lower rates of primary productivity. (Box CC-NPP)	Reduced primary productivity of the ocean impacts fisheries productivity leading to lower catch rates and effects on livelihoods (Section 6.4.1.1; Box CC-NPP)
		Ecosystems and organisms that are sensitive to decreasing oxygen levels (Sections 30.5.2, 30.5.3, 30.5.5, 30.5.6, 30.5.7)	Increased risk of dead (hypoxic) zones reducing key ecosystems and fisheries habitat (Sections 6.1.1.3, 30.3.2.3)	
	Changes to wind, wave height, and storm intensity	Shipping and industrial infrastructure is vulnerable to wave and storm intensity. (Section 30.6.2)	Risk of increasing losses and damages to shipping and industrial infrastructure	Risk of accidents increases for enterprises such as shipping, as well as deep sea oil gas and mineral extraction.

CBS = Coastal Boundary Systems; EBUE = Eastern Boundary Upwelling Ecosystems; EUS = Equatorial Upwelling Systems; HIC, LIC, MIC = high-, low-, and medium-income countries; HLSBS = High-Latitude Spring Bloom Systems; SES = Semi-Enclosed Seas; STG = Sub-Tropical Gyres.

This cross-chapter box should be cited as:

Birkmann, J., R. Licker, M. Oppenheimer, M. Campos, R. Warren, G. Luber, B.C. O'Neill, and K. Takahashi, 2014: Cross-chapter box on a selection of the hazards, key vulnerabilities, key risks, and emergent risks identified in the WGII contribution to the fifth assessment report. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 113-121.

MB

Observed Global Responses of Marine Biogeography, Abundance, and Phenology to Climate Change

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IPCC WGII AR4 presented the detection of a global fingerprint on natural systems and its attribution to climate change (AR4, Chapter 1, SPM Figure 1), but studies from marine systems were mostly absent. Since AR4, there has been a rapid increase in studies that focus on climate change impacts on marine species, which represents an opportunity to move from more anecdotal evidence to examining and potentially attributing detected biological changes within the ocean to climate change (Section 6.3; Figure MB-1). Recent changes in populations of marine species and the associated shifts in diversity patterns are resulting, at least partly, from climate change–mediated biological responses across ocean regions (*robust evidence, high agreement, high confidence*; Sections 6.2, 30.5; Table 6-7).

Poloczanska et al. (2013) assess a potential pattern in responses of ocean life to recent climate change using a global database of 208 peer-reviewed papers. Observed responses (n = 1735) were recorded from 857 species or assemblages across regions and taxonomic groups, from phytoplankton to marine reptiles and mammals (Figure MB-1). Observations were defined as those where the authors of a particular paper assessed the change in a biological parameter (including distribution, phenology, abundance, demography, or community composition) and, if change occurred, the consistency of the change with that expected under climate change. Studies from the peer-reviewed literature were selected using three criteria: (1) authors inferred or directly tested for trends in biological and climatic variables; (2) authors included data after 1990; and (3) observations spanned at least 19 years, to reduce bias resulting from biological responses to short-term climate variability.

The results of this meta-analysis show that climate change has already had widespread impacts on species' distribution, abundance, phenology, and subsequently, species richness and community composition across a broad range of taxonomic groups (plankton to top predators). Of the observations that showed a response in either direction, changes in phenology, distribution and abundance were overwhelmingly (81%) in a direction that was consistent with theoretical responses to climate change (Section 6.2). Knowledge gaps exist, especially in equatorial sub-regions and the Southern Hemisphere (Figure MB-1).

The timing of many biological events (phenology) had an earlier onset. For example, over the last 50 years, spring events shifted earlier for many species with an average advancement of 4.4 ± 0.7 days per decade (mean ± SE) and summer events by 4.4 ± 1.1 days per decade (*robust evidence, high agreement, high confidence*) (Figure MB-2). Phenological observations included in the study range from shifts in peak abundance of phytoplankton and zooplankton, to reproduction and migration of invertebrates, fishes, and seabirds (Sections 6.3.2, 30.5).

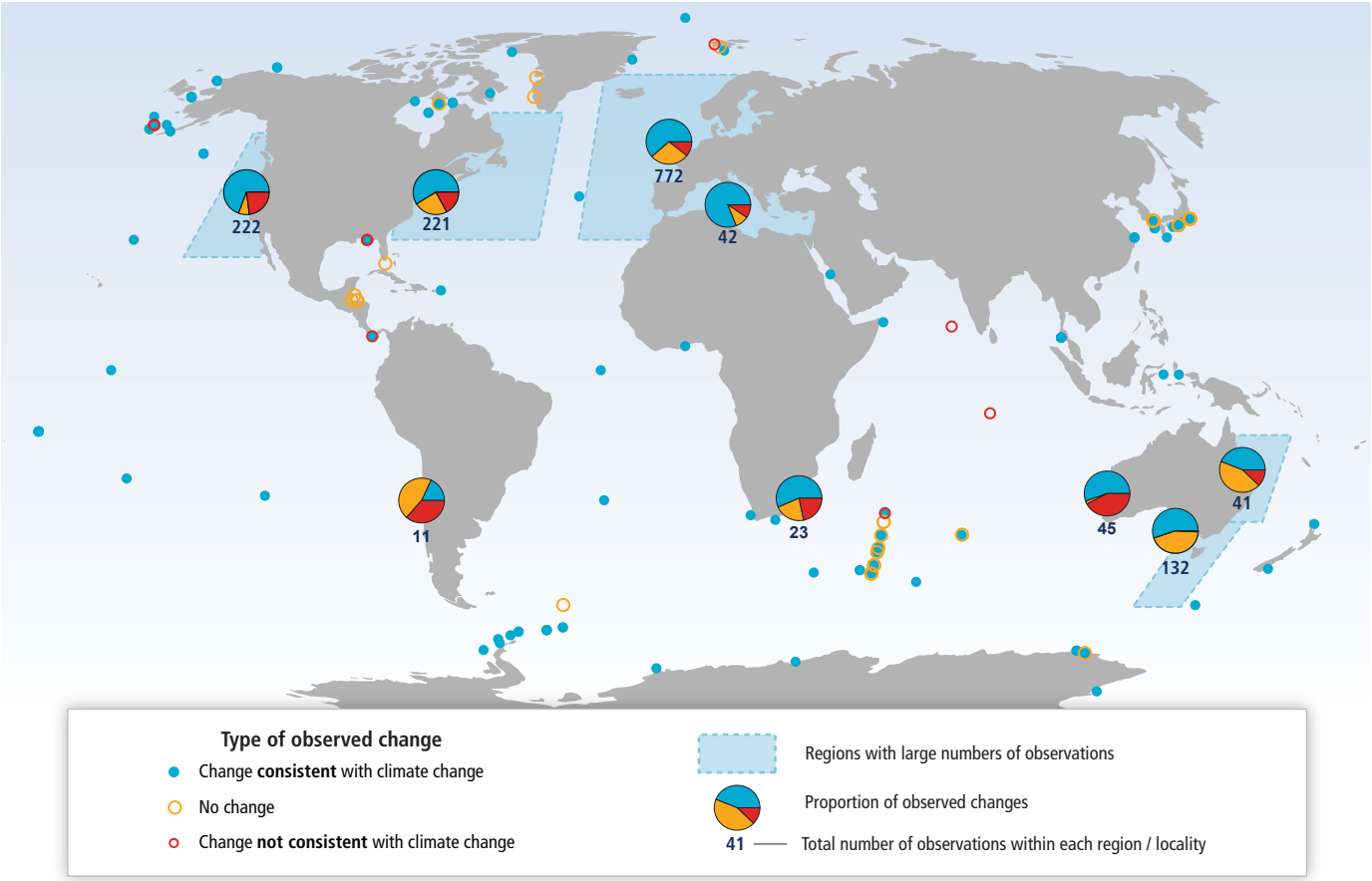

Figure MB-1 | 1735 observed responses to climate change from 208 single- and multi-species studies. Data shown include changes that are attributed (at least partly) to climate change (blue), changes that are inconsistent with climate change (red), and no change (orange). Each circle represents the center of a study area. Where points fall on land, it is because they are centroids of distributions that surround an island or peninsula. Studies encompass areas from single sites (e.g., seabird breeding colony) to large ocean regions (e.g., continuous plankton recorder surveys in north-east Atlantic). For regions (indicated by blue shading) and localities with large numbers of observations, pie charts summarize the relative proportions of the three types of observed changes (consistent with climate change, inconsistent with climate change, and no change) in those regions or localities. The numbers indicate the total observations within each region or locality. Note: 57% of the studies included were published since AR4. (From Poloczanska et al., 2013).

The distributions of benthic, pelagic, and demersal species and communities have shifted by up to a thousand kilometers, although the range shifts have not been uniform across taxonomic groups or ocean regions (Sections 6.3.2, 30.5) (*robust evidence, high agreement, high confidence*). Overall, leading range edges expanded in a poleward direction at 72.0 ± 13.5 km per decade and trailing edges contracted in a poleward direction at 15.8 ± 8.7 km per decade (Figure MB-2), revealing much higher current rates of migration than the potential maximum rates reported for terrestrial species (Figure 4-6) despite slower warming of the ocean than land surface (WGI Section 3.2).

Poleward distribution shifts have resulted in increased species richness in mid- to high-latitude regions (Hiddink and ter Hofstede, 2008) and changing community structure (Simpson et al., 2011; see also Section 28.2.2). Increases in warm-water components of communities concurrent with regional warming have been observed in mid- to high-latitude ocean regions including the Bering Sea, Barents Sea, Nordic Sea, North Sea, and Tasman Sea (Box 6.1; Section 30.5). Observed changes in species composition of catches from 1970–2006 that are partly attributed to long-term ocean warming suggest increasing dominance of warmer water species in subtropical and higher latitude regions, and reduction in abundance of subtropical species in equatorial waters (Cheung et al., 2013), with implications for fisheries (Sections 6.5, 7.4.2, 30.6.2.1).

The magnitude and direction of distribution shifts can be related to temperature velocities (i.e., the speed and direction at which isotherms propagate across the ocean's surface (Section 30.3.1.1; Burrows et al., 2011). Pinsky et al. (2013) showed that shifts in both latitude and depth of benthic fish and crustaceans could be explained by climate velocity with remarkable accuracy, using a database of 128 million individuals across 360 marine taxa from surveys of North American coastal waters conducted over 1968–2011. Poloczanska et al. (2013) found that faster distribution shifts generally occur in regions of highest surface temperature velocity, such as the North Sea and sub-Arctic Pacific Ocean. Observed marine species shifts, since approximately the 1950s, have generally been able to track observed velocities (Figure MB-3), with phyto- and zooplankton distribution shifts vastly exceeding climate velocities observed over most of the ocean surface, but with considerable variability within and among taxonomic groups (Poloczanska et al., 2013).

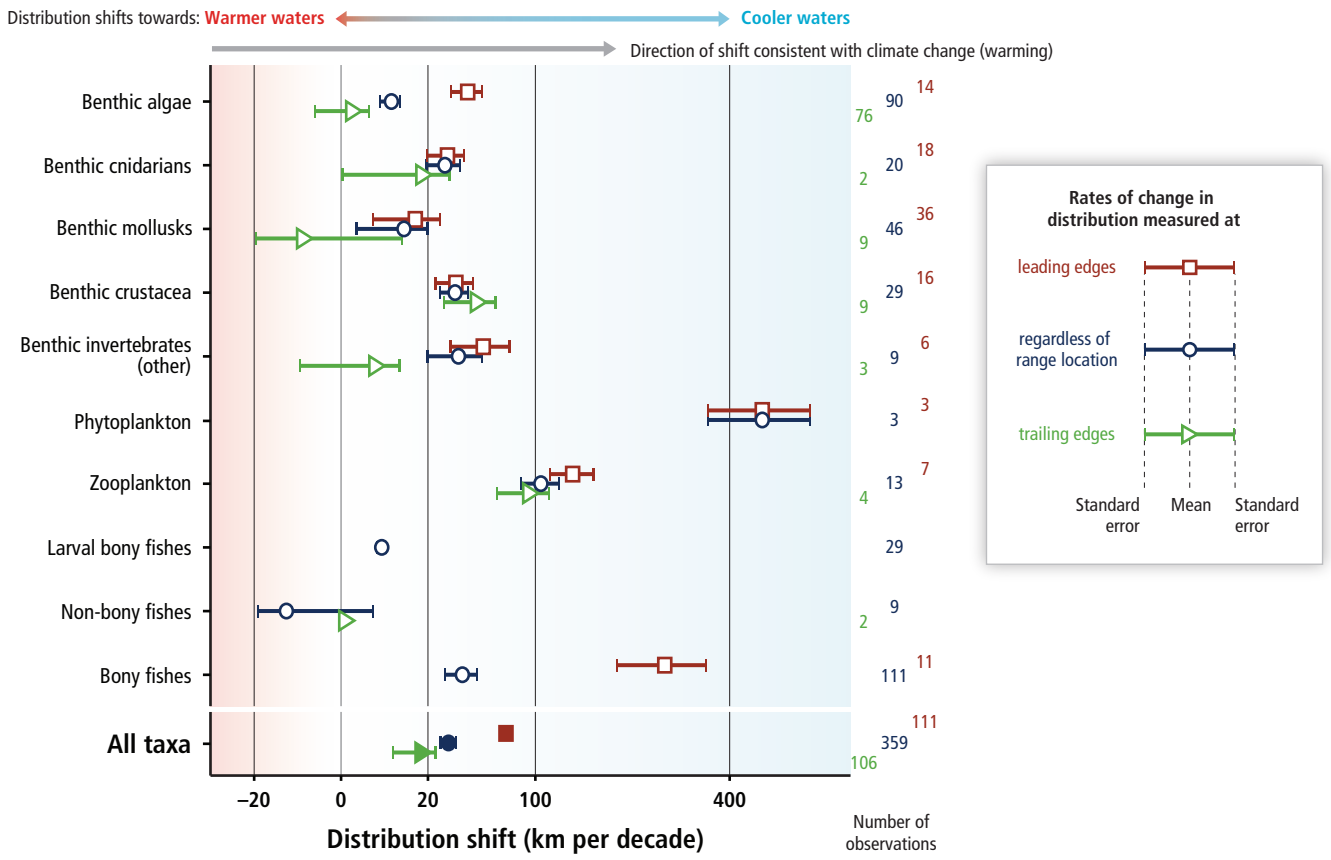

Figure MB-2 | Rates of change in distribution (kilometers per decade) for marine taxonomic groups, measured at the leading edges (red) and trailing edges (green). Average distribution shifts were calculated using all data, regardless of range location, and are in dark blue. Distribution shifts have been square-root transformed; standard errors may be asymmetric as a result. Positive distribution changes are consistent with warming (into previously cooler waters, generally poleward). Means ± standard error are shown, along with number of observations. Non-bony fishes include sharks, rays, lampreys, and hagfish. (From Poloczanska et al., 2013).

Biogeographic shifts are also influenced by other factors such as currents, nutrient and stratification changes, light levels, sea ice, species' interactions, habitat availability and fishing, some of which can be independently influenced by climate change (Section 6.3). Rate and pattern of biogeographic shifts in sedentary organisms and benthic macroalgae are complicated by the influence of local dynamics and topographic features (islands, channels, coastal lagoons, e.g., of the Mediterranean (Bianchi, 2007), coastal upwelling e.g., (Lima et al., 2007)). Geographical barriers constrain range shifts and may cause a loss of endemic species (Ben Rais Lasram et al., 2010), with associated niches filled by alien species, either naturally migrating or artificially introduced (Philippart et al., 2011).

Whether marine species can continue to keep pace as rates of warming, hence climate velocities, increase (Figure MB-3b) is a key uncertainty. Climate velocities on land are expected to outpace the ability of many terrestrial species to track climate velocities this century (Section 4.3.2.5; Figure 4-6). For marine species, the observed rates of shift are generally much faster than those for land species, particularly for primary producers and lower trophic levels (Poloczanska et al., 2013). Phyto- and zooplankton communities (excluding larval fish) have extended distributions at remarkable rates (Figure MB-3b), such as in the Northeast Atlantic (Section 30.5.1) with implications for marine food webs.

Geographical range shifts and depth distribution vary between coexisting marine species (Genner et al., 2004; Perry et al., 2005; Simpson et al., 2011) as a consequence of the width of species-specific thermal windows and associated vulnerabilities (Figure 6-5). Warming therefore causes differential changes in growth, reproductive success, larval output, early juvenile survival, and recruitment, implying shifts in the relative performance of animal species and, thus, their competitiveness (Pörtner and Farrell, 2008; Figure 6-7A). Such effects may underlie abundance losses or local extinctions, "regime shifts" between coexisting species, or critical mismatches between predator and prey organisms, resulting in changes in local and regional species richness, abundance, community composition, productivity, energy flows, and invasion resistance. Even among Antarctic stenotherms, differences in biological responses related to mode of life, phylogeny and associated metabolic capacities exist (Section 6.3.1.4). As a consequence, marine ecosystem functions may be substantially reorganized at the regional scale, potentially triggering a range of cascading effects (Hoegh-Guldberg and Bruno, 2010). A focus on understanding the mechanisms underpinning the nature and magnitude of responses of marine organisms to climate change can help forecast impacts and the associated costs to society as well as facilitate adaptive management strategies formitigating these impacts (Sections 6.3, 6.4).

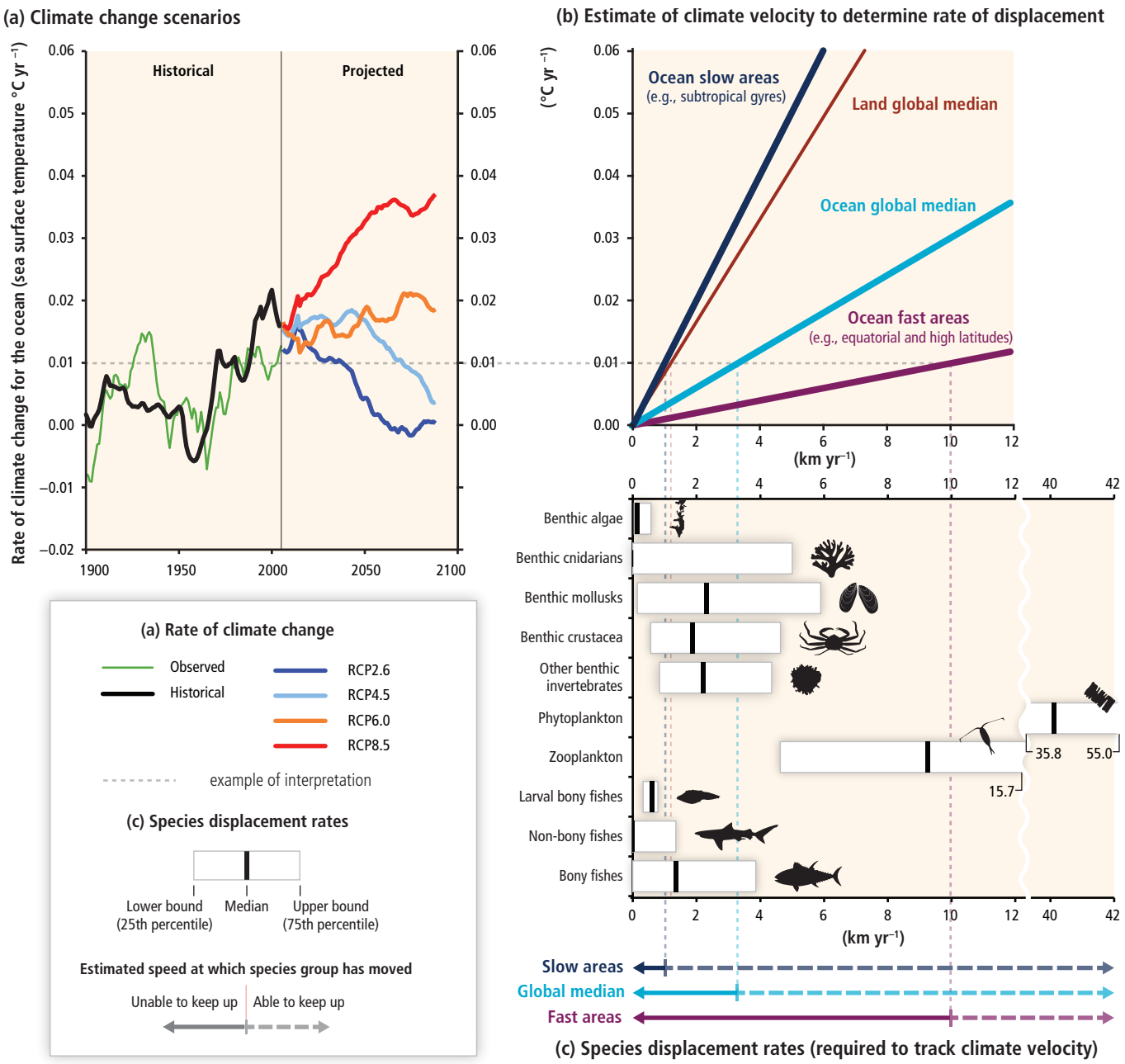

Figure MB-3 | (a) Rate of climate change for the ocean (sea surface temperature (SST) °C yr $^{-1}$). (b) Corresponding climate velocities for the ocean and median velocity from land (adapted from Burrows et al., 2011). (c) Observed rates of displacement of marine taxonomic groups based on observations over 1900–2010. The dotted bands give an example of interpretation. Rates of climate change of 0.01 °C yr^{-1} correspond to approximately 3.3 km yr^{-1} median climate velocity in the ocean. When compared to observed rates of displacement (c), many marine taxonomic groups have been able to track these velocities. For phytoplankton and zooplankton the rates of displacement greatly exceed median climate velocity for the ocean and, for phytoplankton exceed velocities in fast areas of the ocean approximately 10.0 km yr^{-1}. All values are calculated for ocean surface with the exclusion of polar seas (Figure 30-1a). (a) Observed rates of climate change for ocean SST (green line) are derived from the Hadley Centre Interpolated SST 1.1 (HadISST1.1) data set, and all other rates are calculated based on the average of the Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model ensembles (Table SM30-3) for the historical period and for the future based on the four Representative Concentration Pathway (RCP) scenarios. Data were smoothed using a 20-year sliding window. (b) Median climate velocity over the global ocean surface (light blue line; excluding polar seas) calculated from HadSST1.1 data set over 1960–2009 using the methods of Burrows et al. (2011). Median velocities representative of ocean regions of slow velocities such as the Pacific subtropical gyre (dark blue line) and of high velocities such as the Coral Triangle or the North Sea (purple line) shown. Median rates over global land surface (red line) over 1960–2009 calculated using Climate Research Unit data set CRU TS3.1. Figure 30-3 shows climate velocities over the ocean surface calculated over 1960–2009. (c) Rates of displacement for marine taxonomic groups estimated by Poloczanska et al. (2013) using published studies. Note the displacement rates for phytoplankton exceed the axis, so values are given.

References

Ben Rais Lasram, F., F. Guilhaumon, C. Albouy, S. Somot, W. Thuiller, and D. Mouillot, 2010: The Mediterranean Sea as a 'cul-de-sac' for endemic fishes facing climate change. *Global Change Biology*, **16**, 3233-3245.

Bianchi, C.N., 2007: Biodiversity issues for the forthcoming Mediterranean Sea. *Hydrobiologia*, **580**, 7-21.

Burrows, M.T., D. S. Schoeman, L.B. Buckley, P.J. Moore, E.S. Poloczanska, K. Brander, K, C.J. Brown, J.F. Bruno, C.M. Duarte, B.S. Halpern, J. Holding, C.V. Kappel, W. Kiessling, M.I. O'Connor, J.M. Pandolfi, C. Parmesan, F. Schwing, W.J. Sydeman, and A.J. Richardson, 2011: The pace of shifting climate in marine and terrestrial ecosystems. *Science*, **334**, 652-655.

Cheung, W.W.L., R. Watson, and D. Pauly, 2013: Signature of ocean warming in global fisheries catch. *Nature*, **497(7449)**, 365-368.

Genner, M.J., D.W. Sims, V.J. Wearmouth, E.J. Southall, A.J. Southward, P.A. Henderson, and S.J. Hawkins, 2004: Regional climatic warming drives long-term community changes of British marine fish. *Proceedings of the Royal Society B*, **271(1539)**, 655-661.

Hiddink, J.G. and R. ter Hofstede, 2008: Climate induced increases in species richness of marine fishes. *Global Change Biology*, **14**, 453-460.

Hoegh-Guldberg, O. and J.F. Bruno, 2010: The impact of climate change on the world's marine ecosystems. *Science*, **328**, 1523-1528.

Lima, F.P., P.A. Ribeiro, N. Queiroz, S.J. Hawkins, and A.M. Santos, 2007: Do distributional shifts of northern and southern species of algae match the warming pattern? *Global Change Biology*, **13**, 2592-2604.

Perry, A.L., P.J. Low, J.R. Ellis, and J.D. Reynolds, 2005: Climate change and distribution shifts in marine fishes. *Science*, **308(5730)**, 1912-1915.

Philippart, C.J.M., R. Anadon, R. Danovaro, J.W. Dippner, K.F. Drinkwater, S.J. Hawkins, T. Oguz, G. O'Sullivan, and P.C. Reid, 2011: Impacts of climate change on European marine ecosystems: observations, expectations and indicators. *Journal of Experimental Marine Biology and Ecology*, **400**, 52-69.

Pinksy, M.L., B. Worm, M.J. Fogarty, J.L. Sarmiento, and S.A. Levin, 2013: Marine taxa track local climate velocities. *Science*, **341**, 1239-1242.

Pörtner, H.O. and A.P. Farrell, 2008: Physiology and climate change. *Science*, **322(5902)**, 690-692.

Poloczanska, E.S., C.J. Brown, W.J. Sydeman, W. Kiessling, D.S. Schoeman, P.J. Moore, K. Brander, J.F. Bruno, L.B. Buckley, M.T. Burrows, C.M. Duarte, B.S. Halpern, J. Holding, C.V. Kappel, M.I. O'Connor, J.M. Pandolfi, C. Parmesan, F. Schwing, S.A.Thompson, and A.J. Richardson, 2013: Global imprint of climate change on marine life. *Nature Climate Change*, **3**, 919-925.

Simpson, S.D., S. Jennings, M.P. Johnson, J.L. Blanchard, P.J. Schon, D.W. Sims, and M.J. Genner, 2011: Continental shelf-wide response of a fish assemblage to rapid warming of the sea. *Current Biology*, **21**, 1565-1570.

This cross-chapter box should be cited as:

Poloczanska, E.S., O. Hoegh-Guldberg, W. Cheung, H.-O. Pörtner, and M. Burrows, 2014: Cross-chapter box on observed global responses of marine biogeography, abundance, and phenology to climate change. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 123-127.

OA

Ocean Acidification

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Anthropogenic ocean acidification and global warming share the same primary cause, which is the increase of atmospheric CO_2 (Figure OA-1A; WGI, Section 2.2.1). Eutrophication, loss of sea ice, upwelling and deposition of atmospheric nitrogen and sulfur all exacerbate ocean acidification locally (Sections 5.3.3.6, 6.1.1, 30.3.2.2).

Chemistry and Projections

The fundamental chemistry of ocean acidification is well understood (*robust evidence, high agreement*). Increasing atmospheric concentrations of CO_2 result in an increased flux of CO_2 into a mildly alkaline ocean, resulting in a reduction in pH, carbonate ion concentration, and the capacity of seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of the surface layers of the open ocean can be projected at the global scale with high accuracy using projections of atmospheric CO_2 levels (Figure CC-OA-1B). Observations of changing upper ocean CO_2 chemistry over time support this linkage (WGI Table 3.2 and Figure 3.18; Figures 30-8, 30-9). Projected changes in open ocean, surface water chemistry for the year 2100 based on representative concentration pathways (WGI, Figure 6.28) compared to pre-industrial values range from a pH change of –0.14 units with Representative Concentration Pathway (RCP)2.6 (421 ppm CO_2, +1°C, 22% reduction of carbonate ion concentration) to a pH change of –0.43 units with RCP8.5 (936 ppm CO_2, +3.7ºC, 56% reduction of carbonate ion concentration). Projections of regional changes, especially in the highly complex coastal systems (Sections 5.3.3.5, 30.3.2.2), in polar regions (WGI Section 6.4.4), and at depth are more difficult but generally follow similar trends.

Biological, Ecological, and Biogeochemical Impacts

Investigations of the effect of ocean acidification on marine organisms and ecosystems have a relatively short history, recently analyzed in several meta-analyses (Sections 6.3.2.1, 6.3.5.1). A wide range of sensitivities to projected rates of ocean acidification exists within and across diverse groups of organisms, with a trend for greater sensitivity in early life stages (*high confidence*; Sections 5.4.2.2, 5.4.2.4, 6.3.2). A pattern of positive and negative impacts emerges (*high confidence*; Figure OA-1C) but key uncertainties remain in our understanding of the impacts on organisms, life histories, and ecosystems. Responses can be influenced, often exacerbated by other drivers, such as warming, hypoxia, nutrient concentration, and light availability (*high confidence*; Sections 5.4.2.4, 6.3.5).

Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*; Sections 5.4.2.3, 6.3.2.2, 6.3.2.3, 30.5.6). Harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Ocean acidification may stimulate nitrogen fixation (*limited evidence, low agreement*; 6.3.2.2). It decreases the rate of calcification of most, but not

all, sea floor calcifiers (*medium agreement, robust evidence*) such as reef-building corals (Box CC-CR), coralline algae, bivalves, and gastropods, reducing the competitiveness with non-calcifiers (Sections 5.4.2.2, 5.4.2.4, 6.3.2.5). Ocean warming and acidification promote higher rates of calcium carbonate dissolution resulting in the net dissolution of carbonate sediments and frameworks and loss of associated habitat (*medium confidence*; 5.4.2.4, 6.3.2.5, 6.3.5.4). Some corals and temperate fishes experience disturbances to behavior, navigation, and their ability to tell conspecifics from predators (Section 6.3.2.4). However, there is no evidence for these effects to persist on evolutionary time scales in the few groups analyzed (Section 6.3.2).

Some phytoplankton and molluscs displayed adaptation to ocean acidification in long-term experiments (*limited evidence, medium agreement*; Section 6.3.2.1), indicating that the long-term responses could be less than responses obtained in short-term experiments. However, mass extinctions in Earth history occurred during much slower rates of ocean acidification, combined with other drivers changing, suggesting that evolutionary rates are not fast enough for sensitive animals and plants to adapt to the projected rate of future change (*medium confidence*; Section 6.1.2).

Projections of ocean acidification effects at the ecosystem level are made difficult by the diversity of species-level responses. Differential sensitivities and associated shifts in performance and distribution will change predator–prey relationships and competitive interactions (Sections

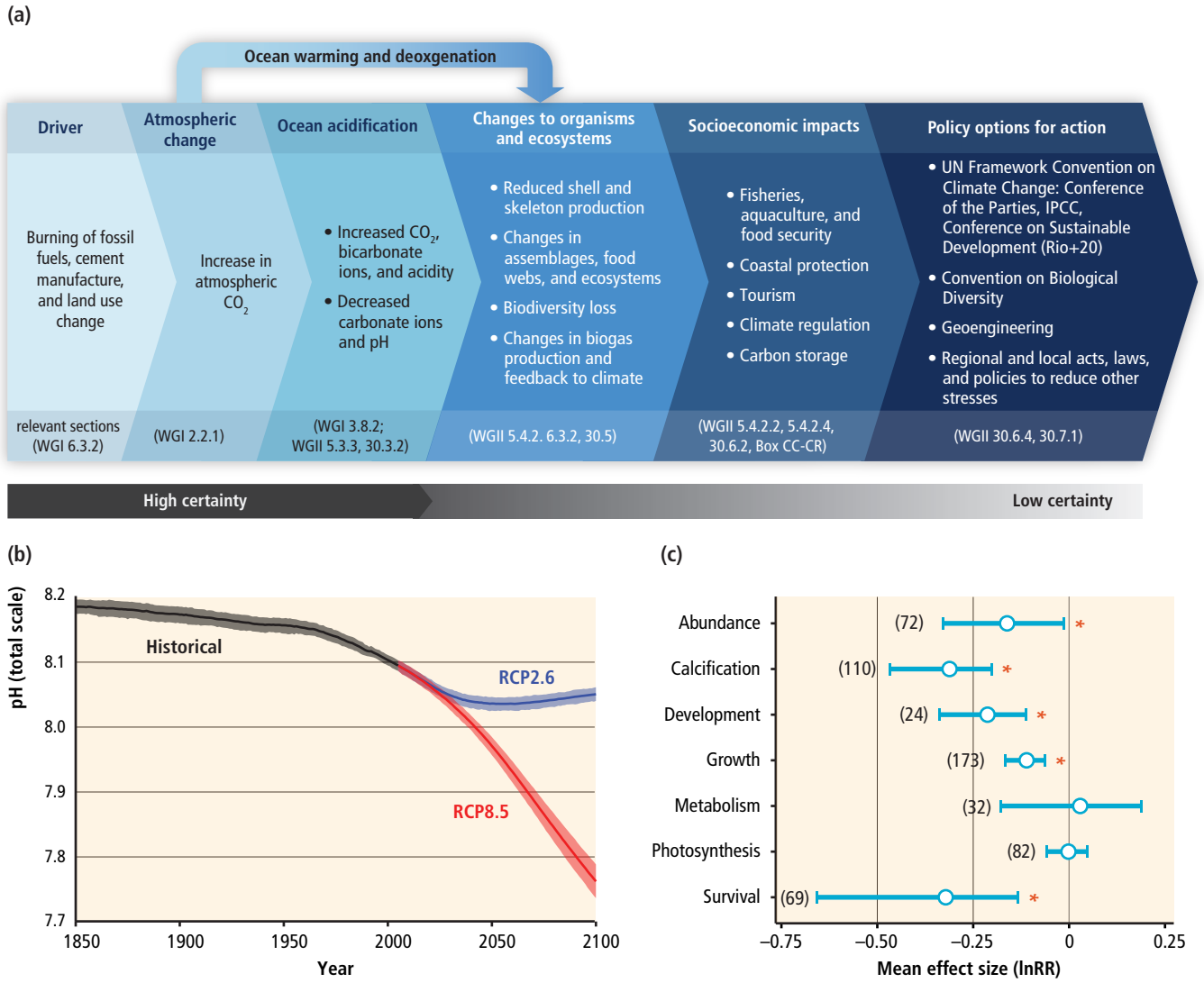

Figure OA-1 | (a) Overview of the chemical, biological, and socio-economic impacts of ocean acidification and of policy options (adapted from Turley and Gattuso, 2012). (b) Multi-model simulated time series of global mean ocean surface pH (on the total scale) from Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model simulations from 1850 to 2100. Projections are shown for emission scenarios Representative Concentration Pathway (RCP)2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (gray shading) is the modeled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations (WGI AR5 Figures SPM.7 and TS.20). (c) Effect of near-future acidification (seawater pH reduction of ≤0.5 units) on major response variables estimated using weighted random effects meta-analyses, with the exception of survival, which is not weighted (Kroeker et al., 2013). The log-transformed response ratio (lnRR) is the ratio of the mean effect in the acidification treatment to the mean effect in a control group. It indicates which process is most uniformly affected by ocean acidification, but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. The * denotes a statistically significant effect.

6.3.2.5, 6.3.5, 6.3.6), which could impact food webs and higher trophic levels (*limited evidence, high agreement*). Natural analogues at CO_2 vents indicate decreased species diversity, biomass, and trophic complexity of communities (Box CC-CR; Sections 5.4.2.3, 6.3.2.5, 30.3.2.2, 30.5). Shifts in community structure have also been documented in regions with rapidly declining pH (Section 5.4.2.2).

Owing to an incomplete understanding of species-specific responses and trophic interactions, the effect of ocean acidification on global biogeochemical cycles is not well understood (*limited evidence, low agreement*) and represents an important knowledge gap. The additive, synergistic, or antagonistic interactions of factors such as temperature, concentrations of oxygen and nutrients, and light are not sufficiently investigated yet.

Risks, Socioeconomic Impacts, and Costs

The risks of ocean acidification to marine organisms, ecosystems, and ultimately to human societies, include both the probability that ocean acidification will affect fundamental physiological and ecological processes of organisms (Section 6.3.2.1), and the magnitude of the resulting impacts on ecosystems and the ecosystem services they provide to society (Box 19-2). For example, ocean acidification under RCP4.5 to RCP8.5 will impact formation and maintenance of coral reefs (*high confidence*; Box CC-CR, Section 5.4.2.4) and the goods and services that they provide such as fisheries, tourism, and coastal protection (*limited evidence, high agreement*; Box CC-CR; Sections 6.4.1.1,19.5.2, 27.3.3, 30.5, 30.6). Ocean acidification poses many other potential risks, but these cannot yet be quantitatively assessed because of the small number of studies available, particularly on the magnitude of the ecological and socioeconomic impacts (Section 19.5.2).

Global estimates of observed or projected economic costs of ocean acidification do not exist. The largest uncertainty is how the impacts on lower trophic levels will propagate through the food webs and to top predators. However, there are a number of instructive examples that illustrate the magnitude of potential impacts of ocean acidification. A decrease of the production of commercially exploited shelled molluscs (Section 6.4.1.1) would result in a reduction of USA production of 3 to 13% according to the Special Report on Emission Scenarios (SRES) A1FI emission scenario (*low confidence*). The global cost of production loss of molluscs could be more than US$100 billion by 2100 (*limited evidence, medium agreement*). Models suggest that ocean acidification will generally reduce fish biomass and catch (*low confidence*) and that complex additive, antagonistic, and/or synergistic interactions will occur with other environmental (warming) and human (fisheries management) factors (Section 6.4.1.1). The annual economic damage of ocean-acidification–induced coral reef loss by 2100 has been estimated, in 2012, to be US$870 and 528 billion, respectively for the A1 and B2 SRES emission scenarios (*low confidence*; Section 6.4.1). Although this number is small compared to global gross domestic product (GDP), it can represent a very large GDP loss for the economies of many coastal regions or small islands that rely on the ecological goods and services of coral reefs (Sections 25.7.5, 29.3.1.2).

Mitigation and Adaptation

Successful management of the impacts of ocean acidification includes two approaches: mitigation of the source of the problem (i.e., reduce anthropogenic emissions of CO_2) and/or adaptation by reducing the consequences of past and future ocean acidification (Section 6.4.2.1). Mitigation of ocean acidification through reduction of atmospheric CO_2 is the most effective and the least risky method to limit ocean acidification and its impacts (Section 6.4.2.1). Climate geoengineering techniques based on solar radiation management will not abate ocean acidification and could increase it under some circumstances (Section 6.4.2.2). Geoengineering techniques to remove CO_2 from the atmosphere could directly address the problem but are very costly and may be limited by the lack of CO_2 storage capacity (Section 6.4.2.2). In addition, some ocean-based approaches, such as iron fertilization, would only relocate ocean acidification from the upper ocean to the ocean interior, with potential ramifications on deep water oxygen levels (Sections 6.4.2.2, 30.3.2.3, 30.5.7). A low-regret approach, with relatively limited effectiveness, is to limit the number and the magnitude of drivers other than CO_2, such as nutrient pollution (Section 6.4.2.1). Mitigation of ocean acidification at the local level could involve the reduction of anthropogenic inputs of nutrients and organic matter in the coastal ocean (Section 5.3.4.2). Some adaptation strategies include drawing water for aquaculture from local watersheds only when pH is in the right range, selecting for less sensitive species or strains, or relocating industries elsewhere (Section 6.4.2.1).

References

Kroeker, K., R.C. Kordas, A. Ryan, I. Hendriks, L. Ramajo, G. Singh, C. Duarte, and J.-P. Gattuso, 2013: Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. *Global Change Biology*, **19**, 1884-1896.

Turley, C. and J.-P. Gattuso, 2012: Future biological and ecosystem impacts of ocean acidification and their socioeconomic-policy implications. *Current Opinion in Environmental Sustainability*, **4**, 278-286.

This cross-chapter box should be cited as:

Gattuso, J.-P., P.G. Brewer, O. Hoegh-Guldberg, J.A. Kleypas, H.-O. Pörtner, and D.N. Schmidt, 2014: Cross-chapter box on ocean acidification. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 129-131.

PP

Net Primary Production in the Ocean

Philip W. Boyd (New Zealand), Svein Sundby (Norway), Hans-Otto Pörtner (Germany)

Net Primary Production (NPP) is the rate of photosynthetic carbon fixation minus the fraction of fixed carbon used for cellular respiration and maintenance by autotrophic planktonic microbes and benthic plants (Sections 6.2.1, 6.3.1). Environmental drivers of NPP include light, nutrients, micronutrients, CO_2, and temperature (Figure PP-1a). These drivers, in turn, are influenced by oceanic and atmospheric processes, including cloud cover; sea ice extent; mixing by winds, waves, and currents; convection; density stratification; and various forms of upwelling induced by eddies, frontal activity, and boundary currents. Temperature has multiple roles as it influences rates of phytoplankton physiology and heterotrophic bacterial recycling of nutrients, in addition to stratification of the water column and sea ice extent (Figure PP-1a). Climate change is projected to strongly impact NPP through a multitude of ways that depend on the regional and local physical settings (WGI AR5, Chapter 3), and on ecosystem structure and functioning (*medium confidence*; Sections 6.3.4, 6.5.1). The influence of environmental drivers on NPP causes as much as a 10-fold variation in regional productivity with nutrient-poor subtropical waters and light-limited Arctic waters at the lower range and productive upwelling regions and highly eutrophic coastal regions at the upper range (Figure PP-1b).

The oceans currently provide ~50×10^{15} g C yr^{-1}, or about half of global NPP (Field et al., 1998). Global estimates of NPP are obtained mainly from satellite remote sensing (Section 6.1.2), which provides unprecedented spatial and temporal coverage, and may be validated regionally against oceanic measurements. Observations reveal significant changes in rates of NPP when environmental controls are altered by episodic natural perturbations, such as volcanic eruptions enhancing iron supply, as observed in high-nitrate low-chlorophyll waters of the Northeast Pacific (Hamme et al., 2010). Climate variability can drive pronounced changes in NPP (Chavez et al., 2011), such as from El Niño to La Niña transitions in Equatorial Pacific, when vertical nutrient and trace element supply are enhanced (Chavez et al., 1999).

Multi-year time series records of NPP have been used to assess spatial trends in NPP in recent decades. Behrenfeld et al. (2006), using satellite data, reported a prolonged and sustained global NPP decrease of 190×10^{12} g C yr^{-1}, for the period 1999–2005—an annual reduction of 0.57% of global NPP. In contrast, a time series of directly measured NPP between 1988 and 2007 by Saba et al. (2010) (i.e., *in situ* incubations using the radiotracer ^{14}C-bicarbonate) revealed an increase (2% yr^{-1}) in NPP for two low-latitude open ocean sites. This discrepancy between *in situ* and remotely sensed NPP trends points to uncertainties in either the methodology used and/or the extent to which discrete sites are representative of oceanic provinces (Saba et al., 2010, 2011). Modeling studies have subsequently revealed that the <15-year archive of satellite-

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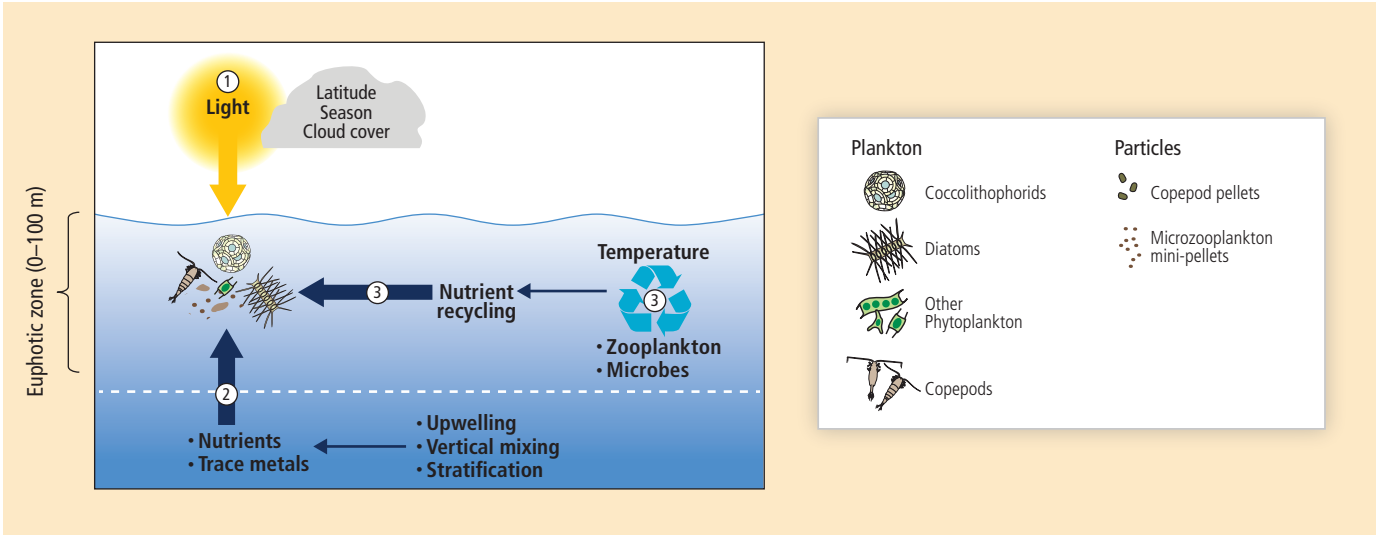

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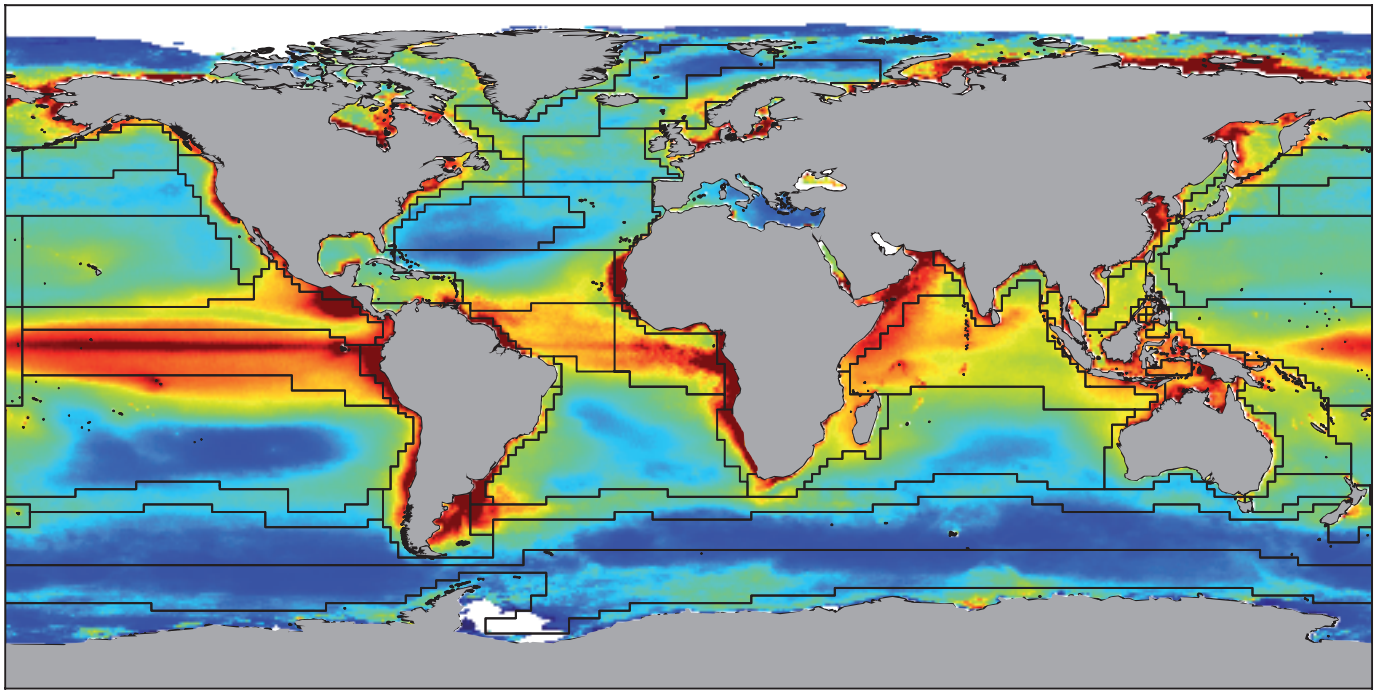

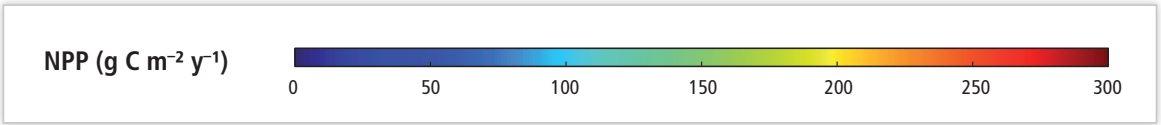

Figure PP-1 | (a) Environmental factors controlling Net Primary Production (NPP). NPP is controlled mainly by three basic processes: (1) light conditions in the surface ocean, that is, the photic zone where photosynthesis occurs; (2) upward flux of nutrients and micronutrients from underlying waters into the photic zone, and (3) regeneration of nutrients and micronutrients via the breakdown and recycling of organic material before it sinks out of the photic zone. All three processes are influenced by physical, chemical, and biological processes and vary across regional ecosystems. In addition, water temperature strongly influences the upper rate of photosynthesis for cells that are resource-replete. Predictions of alteration of primary productivity under climate change depend on correct parameterizations and simulations of each of these variables and processes for each region. (b) Annual composite map of global areal NPP rates (derived from Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua satellite climatology from 2003–2012; NPP was calculated with the Carbon-based Productivity Model (CbPM; Westberry et al., 2008)). Overlaid is a grid of (thin black lines) that represent 51 distinct global ocean biogeographical provinces (after Longhurst, 1998 and based on Boyd and Doney, 2002). The characteristics and boundaries of each province are primarily set by the underlying regional ocean physics and chemistry. White areas = no data. (Figure courtesy of Toby Westberry (OSU) and Ivan Lima (WHOI), satellite data courtesy of NASA Ocean Biology Processing Group.)

derived NPP is insufficient to distinguish climate-change mediated shifts in NPP from those driven by natural climate variability (Henson et al., 2010; Beaulieu et al., 2013). Although multi-decadal, the available time series of oceanic NPP measurements are also not of sufficient duration relative to the time scales of longer-term climate variability modes as for example Atlantic Multi-decadal Oscillation (AMO), with periodicity of 60-70 years, Figure 6-1). Recent attempts to synthesize longer (i.e., centennial) records of chlorophyll as a proxy for phytoplankton stocks (e.g., Boyce et al., 2010) have been criticized for relying on questionable linkages between different proxies for chlorophyll over a century of records (e.g., Rykaczewski and Dunne, 2011).

Models in which projected climate change alters the environmental drivers of NPP provide estimates of spatial changes and of the rate of change of NPP. For example, four global coupled climate–ocean biogeochemical Earth System Models (WGI AR5 Chapter 6) projected an increase in NPP at high latitudes as a result of alleviation of light and temperature limitation of NPP, particularly in the high-latitude biomes (Steinacher et al., 2010). However, this regional increase in NPP was more than offset by decreases in NPP at lower latitudes and at mid-latitudes due to the reduced input of macronutrients into the photic zone. The reduced mixed-layer depth and reduced rate of circulation may cause a decrease in the flux of macronutrients to the euphotic zone (Figure 6-2). These changes to oceanic conditions result in a reduction in global mean NPP by 2 to 13% by 2100 relative to 2000 under a high emission scenario (Polovina et al., 2011; SRES (Special Report on Emission Scenarios) A2, between RCP6.0 and RCP8.5). This is consistent with a more recent analysis based on 10 Earth System Models (Bopp et al., 2013), which project decreases in global NPP by 8.6 (±7.9), 3.9 (±5.7), 3.6 (±5.7), and 2.0 (±4.1) % in the 2090s relative to the 1990s, under the scenarios RCP8.5, RCP6.0, RCP4.5, and RCP2.6, respectively. However, the magnitude of projected changes varies widely between models (e.g., from 0 to 20% decrease in NPP globally under RCP 8.5). The various models show very large differences in NPP at regional scales (i.e., provinces, see Figure PP-1b).

Model projections had predicted a range of changes in global NPP from an increase (relative to preindustrial rates) of up to 8.1% under an intermediate scenario (SRES A1B, similar to RCP6.0; Sarmiento et al., 2004; Schmittner et al., 2008) to a decrease of 2-20% under the SRES A2 emission scenario (Steinacher et al., 2010). These projections did not consider the potential contribution of primary production derived from atmospheric nitrogen fixation in tropical and subtropical regions, favoured by increasing stratification and reduced nutrient inputs from mixing. This mechanism is potentially important, although such episodic increases in nitrogen fixation are not sustainable without the presence of excess phosphate (e.g., Moore et al., 2009; Boyd et al., 2010). This may lead to an underestimation of NPP (Mohr et al., 2010; Mulholland et al., 2012; Wilson et al., 2012), however, the extent of such underestimation is unknown (Luo et al., 2012).

Care must be taken when comparing global, provincial (e.g., low-latitude waters, e.g., Behrenfeld et al., 2006) and regional trends in NPP derived from observations, as some regions have additional local environmental influences such as enhanced density stratification of the upper ocean from melting sea ice. For example, a longer phytoplankton growing season, due to more sea ice–free days, may have increased NPP (based on a regionally validated time-series of satellite NPP) in Arctic waters (Arrigo and van Dijken, 2011) by an average of 8.1×10^{12} g C yr^{-1} between 1998 and 2009. Other regional trends in NPP are reported in Sections 30.5.1 to 30.5.6. In addition, although future model projections of global NPP from different models (Steinacher et al., 2010; Bopp et al., 2013) are comparable, regional projections from each of the models differ substantially. This raises concerns as to which aspect(s) of the different model NPP parameterizations are responsible for driving regional differences in NPP, and moreover, how accurate model projections are of global NPP.

From a global perspective, open ocean NPP will decrease moderately by 2100 under both low- (SRES B1 or RCP4.5) and high-emission scenarios (*medium confidence*; SRES A2 or RCPs 6.0, 8.5, Sections 6.3.4, 6.5.1), paralleled by an increase in NPP at high latitudes and a decrease in the tropics (*medium confidence*). However, there is *limited evidence* and *low agreement* on the direction, magnitude and differences of a change of NPP in various ocean regions and coastal waters projected by 2100 (*low confidence*).

References

Arrigo, K.R. and G.L. van Dijken, 2011: Secular trends in Arctic Ocean net primary production. *Journal of Geophysical Research*, **116(C9)**, C09011, doi:10.1029/2011JC007151.

Beaulieu, C., S.A. Henson, J.L. Sarmiento, J.P. Dunne, S.C. Doney, R.R. Rykaczewski, and L. Bopp, 2013: Factors challenging our ability to detect long-term trends in ocean chlorophyll. *Biogeosciences*, **10(4)**, 2711-2724.

Behrenfeld, M.J., R.T. O'Malley, D.A. Siegel, C.R. McClain, J.L. Sarmiento, G.C. Feldman, A.J. Milligan, P.G. Falkowski, R.M. Letelier, and E.S. Boss, 2006: Climate-driven trends in contemporary ocean productivity. *Nature*, **444(7120)**, 752-755.

Bopp, L., L. Resplandy, J.C. Orr, S.C. Doney, J.P. Dunne, M. Gehlen, P. Halloran, C. Heinze, T. Ilyina, R. Séférian, J. Tijiputra, and M. Vichi, 2013: Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. *Biogeosciences*, **10**, 6225-6245.

Boyce, D.G., M.R. Lewis, and B. Worm, 2010: Global phytoplankton decline over the past century. *Nature*, **466(7306)**, 591-596.

Boyd, P.W. and S.C. Doney, 2002: Modelling regional responses by marine pelagic ecosystems to global climate change. *Geophysical Research Letters*, **29(16)**, 53-1–53-4, doi:10.1029/2001GL014130.

Boyd, P.W., R. Strzepek, F.X. Fu, and D.A. Hutchins, 2010: Environmental control of open-ocean phytoplankton groups: now and in the future. *Limnology and Oceanography*, **55(3)**, 1353-1376.

Chavez, F.P., P.G. Strutton, C.E. Friederich, R.A. Feely, G.C. Feldman, D.C. Foley, and M.J. McPhaden, 1999: Biological and chemical response of the equatorial Pacific Ocean to the 1997-98 El Niño. *Science*, **286(5447)**, 2126-2131.

Chavez, F.P., M. Messié, and J.T. Pennington, 2011: Marine primary production in relation to climate variability and change. *Annual Review of Marine Science*, **3(1)**, 227-260.

Field, C.B., M.J. Behrenfeld, J.T. Randerson, and P. Falkowski, 1998: Primary production of the biosphere: integrating terrestrial and oceanic components. *Science*, **281(5374)**, 237-240.

Hamme, R.C., P.W. Webley, W.R. Crawford, F.A. Whitney, M.D. DeGrandpre, S.R. Emerson, C.C. Eriksen, K.E. Giesbrecht, J.F.R. Gower, M.T. Kavanaugh, M.A. Peña, C.L. Sabine, S.D. Batten, L.A. Coogan, D.S. Grundle, and D. Lockwood, 2010: Volcanic ash fuels anomalous plankton bloom in subarctic northeast Pacific. *Geophysical Research Letters*, **37(19)**, L19604, doi:10.1029/2010GL044629.

Henson, S.A., J.L. Sarmiento, J.P. Dunne, L. Bopp, I. Lima, S.C. Doney, J. John, and C. Beaulieu, 2010: Detection of anthropogenic climate change in satellite records of ocean chlorophyll and productivity. *Biogeosciences*, **7(2)**, 621-640.

Longhurst, A.R., 1998: *Ecological Geography of the Sea*. Academic Press, San Diego, CA, USA, 560 pp.

Luo, Y.-W., S.C. Doney, L.A. Anderson, M. Benavides, I. Berman-Frank, A. Bode, S. Bonnet, K.H. Boström, D. Böttjer, D.G. Capone, E.J. Carpenter, Y.L. Chen, M.J. Church, J.E. Dore, L.I. Falcón, A. Fernández, R.A. Foster, K. Furuya, F. Gómez, K. Gundersen, A.M. Hynes, D.M. Karl, S. Kitajima, R.J. Langlois, J. LaRoche, R.M. Letelier, E. Marañón, D.J. McGillicuddy Jr., P.H. Moisander, C.M. Moore, B. Mouriño-Carballido, M.R. Mulholland, J.A. Needoba, K.M. Orcutt, A.J. Poulton, E. Rahav, P. Raimbault, A.P. Rees, L. Riemann, T. Shiozaki, A. Subramaniam, T. Tyrrell, K.A. Turk-Kubo, M. Varela, T.A. Villareal, E.A. Webb, A.E. White, J. Wu, and J.P. Zehr, 2012: Database of diazotrophs in global ocean: abundances, biomass and nitrogen fixation rates. *Earth System Science Data*, **4**, 47-73, doi:10.5194/essd-4-47-2012.

Mohr, W., T. Großkopf, D.W.R. Wallace, and J. LaRoche, 2010: Methodological underestimation of oceanic nitrogen fixation rates. *PLoS ONE*, **5(9)**, e12583, doi:10.1371/journal.pone.0012583.

Moore, C.M., M.M. Mills, E.P. Achterberg, R.J. Geider, J. LaRoche, M.I. Lucas, E.L. McDonagh, X. Pan, A.J. Poulton, M.J.A. Rijkenberg, D.J. Suggett, S.J. Ussher, and E.M.S. Woodward, 2009: Large-scale distribution of Atlantic nitrogen fixation controlled by iron availability. *Nature Geoscience*, **2(12)**, 867-871.

Mulholland, M.R., P.W. Bernhardt, J.L. Blanco-Garcia, A. Mannino, K. Hyde, E. Mondragon, K. Turk, P.H. Moisander, and J.P. Zehr, 2012: Rates of dinitrogen fixation and the abundance of diazotrophs in North American coastal waters between Cape Hatteras and Georges Bank. *Limnology and Oceanography*, **57(4)**, 1067-1083.

Polovina, J.J., J.P. Dunne, P.A. Woodworth, and E.A. Howell, 2011: Projected expansion of the subtropical biome and contraction of the temperate and equatorial upwelling biomes in the North Pacific under global warming. *ICES Journal of Marine Science*, **68(6)**, 986-995.

Rykaczewski, R.R. and J.P. Dunne, 2011: A measured look at ocean chlorophyll trends. *Nature*, **472(7342)**, E5-E6, doi:10.1038/nature09952.

Saba, V.S., M.A.M. Friedrichs, M.-E. Carr, D. Antoine, R.A. Armstrong, I. Asanuma, O. Aumont, N.R. Bates, M.J. Behrenfeld, V. Bennington, L. Bopp, J. Bruggeman, E.T. Buitenhuis, M.J. Church, A.M. Ciotti, S.C. Doney, M. Dowell, J. Dunne, S. Dutkiewicz, W. Gregg, N. Hoepffner, K.J.W. Hyde, J. Ishizaka, T. Kameda, D.M. Karl, I. Lima, M.W. Lomas, J. Marra, G.A. McKinley, F. Mélin, J.K. Moore, A. Morel, J. O'Reilly, B. Salihoglu, M. Scardi, T.J. Smyth, S.L. Tang, J. Tjiputra, J. Uitz, M. Vichi, K. Waters, T.K. Westberry, and A. Yool, 2010: Challenges of modeling depth-integrated marine primary productivity over multiple decades: a case study at BATS and HOT. *Global Biogeochemical Cycles*, **24**, GB3020, doi:10.1029/2009GB003655.

Saba, V.S., M.A.M. Friedrichs, D. Antoine, R.A. Armstrong, I. Asanuma, M.J. Behrenfeld, A.M. Ciotti, M. Dowell, N. Hoepffner, K.J.W. Hyde, J. Ishizaka, T. Kameda, J. Marra, F. Mélin, A. Morel, J. O'Reilly, M. Scardi, W.O. Smith Jr., T.J. Smyth, S. Tang, J. Uitz, K. Waters, and T.K. Westberry, 2011: An evaluation of ocean color model estimates of marine primary productivity in coastal and pelagic regions across the globe. *Biogeosciences*, **8(2)**, 489-503.

Sarmiento, J.L., R. Slater, R. Barber, L. Bopp, S.C. Doney, A.C. Hirst, J. Kleypas, R. Matear, U. Mikolajewicz, P. Monfray, V. Soldatov, S.A. Spall, and R. Stouffer, 2004: Response of ocean ecosystems to climate warming. *Global Biogeochemical Cycles*, **18(3)**, GB3003, doi:10.1029/2003GB002134.

Schmittner, A., A. Oschlies, H.D. Matthews, and E.D. Galbraith, 2008: Future changes in climate, ocean circulation, ecosystems, and biogeochemical cycling simulated for a business-as-usual CO2 emission scenario until year 4000 AD. *Global Biogeochemical Cycles*, **22(1)**, GB1013, doi:10.1029/2007GB002953.

Steinacher, M., F. Joos, T.L. Frölicher, L. Bopp, P. Cadule, V. Cocco, S.C. Doney, M. Gehlen, K. Lindsay, J.K. Moore, B. Schneider, and J. Segschneider, 2010: Projected 21st century decrease in marine productivity: a multi-model analysis. *Biogeosciences*, **7(3)**, 979-1005.

Westberry, T., M.J. Behrenfeld, D.A Siegel, and E. Boss, 2008: Carbon-based primary productivity modeling with vertically resolved photoacclimation. *Global Biogeochemical Cycles*, **22(2)**, GB2024, doi:10.1029/2007GB003078.

Wilson, S.T., D. Böttjer, M.J. Church, and D.M. Karl, 2012: Comparative assessment of nitrogen fixation methodologies, conducted in the oligotrophic North Pacific Ocean. *Applied and Environmental Microbiology*, **78(18)**, 6516-6523.

This cross-chapter box should be cited as:

Boyd, P.W., S. Sundby, and H.-O. Pörtner, 2014: *Cross-chapter box on net primary production in the ocean. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 133-136.

RC

Regional Climate Summary Figures

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Information about the likelihood of regional climate change, assessed by Working Group I (WGI), is foundational for the Working Group II assessment of climate-related risks. To help communicate this assessment, the regional chapters of WGII present a coordinated set of regional climate figures, which summarize observed and projected change in annual average temperature and precipitation during the near term and the longer term for RCP2.6 and RCP8.5. These WGII regional climate summary figures use the same temperature and precipitation fields that are assessed in WGI Chapter 2 and WGI Chapter 12, with spatial boundaries, uncertainty metrics, and data classes tuned to support the WGII assessment of climate-related risks and options for risk management. Additional details on regional climate and regional climate processes can be found in WGI Chapter 14 and WGI Annex 1.

The WGII maps of observed annual temperature and precipitation use the same source data, calculations of data sufficiency, and calculations of trend significance as WGI Chapter 2 and WGI Figures SPM.1 and SPM.2. (A full description of the observational data selection and significance testing can be found in WGI Box 2.2.) Observed trends are determined by linear regression over the 1901–2012 period of Merged Land–Ocean Surface Temperature (MLOST) for annual temperature, and over the 1951–2010 period of Global Precipitation Climatology Centre (GPCC) for annual precipitation. Data points on the maps are classified into three categories, reflecting the categories used in WGI Figures SPM.1 and SPM.2:

1) Solid colors indicate areas where (a) sufficient data exist to permit a robust estimate of the trend (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period), and (b) the trend is significant at the 10% level (after accounting for autocorrelation effects on significance testing).
2) Diagonal lines indicate areas where sufficient data exist to permit a robust estimate of the trend, but the trend is not significant at the 10% level.
3) White indicates areas where there are not sufficient data to permit a robust estimate of the trend.

The WGII maps of projected annual temperature and precipitation are based on the climate model simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012), which also form the basis for the figures presented in WGI (including WGI Chapters 12, 14, and Annex I). The CMIP5 archive includes output from Atmosphere–Ocean General Circulation Models (AOGCMs), AOGCMs with coupled vegetation and/or carbon cycle components, and AOGCMs with coupled atmospheric chemistry components. The number of models from which output is available, and the number of realizations of each model, vary between the different CMIP5 experiments. The WGII regional climate maps use the same source data as WGI Chapter 12 (e.g., Box 12.1 Figure

1), including the WGI multi-model mean values; the WGI individual model values; the WGI measure of baseline ("internal") variability; and the WGI time periods for the reference (1986–2005), mid-21st century (2046–2065), and late-21st century (2081–2100) periods. The full description of the selection of models, the selection of realizations, the definition of internal variability, and the interpolation to a common grid can be found in WGI Chapter 12 and Annex I.

In contrast to the Coupled Model Intercomparison Project Phase 3 (CMIP3) (Meehl et al., 2007), which used the IPCC Special Report on Emission Scenarios (SRES) emission scenarios (IPCC, 2000), CMIP5 uses the Representative Concentration Pathways (RCPs) (van Vuuren et al., 2011) to characterize possible trajectories of climate forcing over the 21st century. The WGII regional climate projection maps include RCP2.6 and RCP8.5, which represent the high and low end of the RCP range at the end of the 21st century. Projected changes in global mean temperature are similar across the RCPs over the next few decades (Figure RC-1; WGI Figure 12.5). During this near-term era of committed climate change, risks will evolve as socioeconomic trends interact with the changing climate. In addition, societal responses, particularly adaptations, will influence near-term outcomes. In the second half of the 21st century and beyond, the magnitude of global temperature increase diverges across the RCPs (Figure RC-1; WGI Figure 12.5). For this longer-term era of climate options, near-term and longer-term mitigation and adaptation, as well as development pathways, will determine the risks of climate change. The benefits of mitigation and adaptation thereby occur over different but overlapping time frames, and present-day choices thus affect the risks of climate change throughout the 21st century.

The projection maps plot differences in annual average temperature and precipitation between the future and reference periods (Figures RC-2 and RC-3), categorized into four classes. The classes are constructed based on the IPCC uncertainty guidance, providing a quantitative basis for assigning likelihood (Mastrandrea et al., 2010), with *likely* defined as 66 to 100% and *very likely* defined as 90 to 100%.

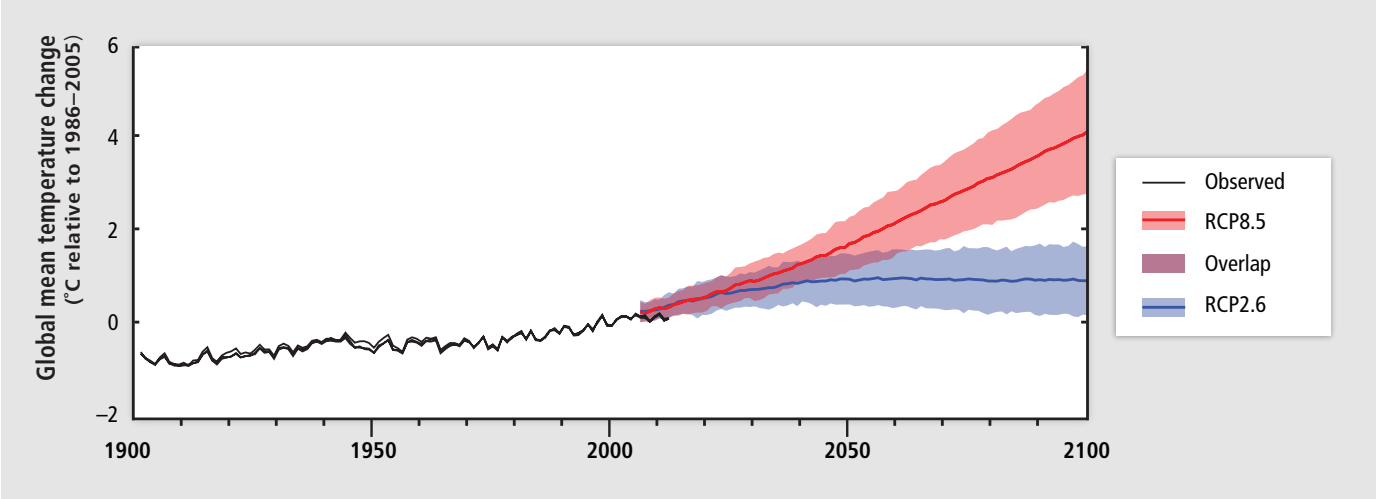

Figure RC-1 | Observed and projected changes in global annual average temperature. Values are expressed relative to 1986–2005. Black lines show the Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP), National Climate Data Center Merged Land–Ocean Surface Temperature (NCDC-MLOST), and Hadley Centre/Climatic Research Unit gridded surface temperature data set 4.2 (HadCRUT4.2) estimates from observational measurements. Blue and red lines and shading denote the ensemble mean and ±1.64 standard deviation range, based on Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations from 32 models for Representative Concentration Pathway (RCP) 2.6 and 39 models for RCP8.5.

The classifications in the WGII regional climate projection figures are based on two aspects of likelihood (e.g., WGI Box 12.1 and Knutti et al., 2010). The first is the likelihood that projected changes exceed differences arising from internal climate variability (e.g., Tebaldi et al., 2011). The second is agreement among models on the sign of change (e.g., Christensen et al., 2007; and IPCC, 2012).

The four classifications of projected change depicted in the WGII regional climate maps are:

1) Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-year means), and greater than or equal to 90% of models agree on sign of change. These criteria (and the areas that fall into this category) are identical to the highest confidence category in WGI Box 12.1. This category supersedes other categories in the WGII regional climate maps.
2) Colors with white dots indicate areas with strong agreement, where 66% or more of models show change greater than the baseline variability, and 66% or more of models agree on sign of change.
3) Gray indicates areas with divergent changes, where 66% or more of models show change greater than the baseline variability, but fewer than 66% agree on sign of change.
4) Colors with diagonal lines indicate areas with little or no change, where fewer than 66% of models show change greater than the baseline variability. It should be noted that areas that fall in this category for the annual average could still exhibit significant change at seasonal, monthly, and/or daily time scales.

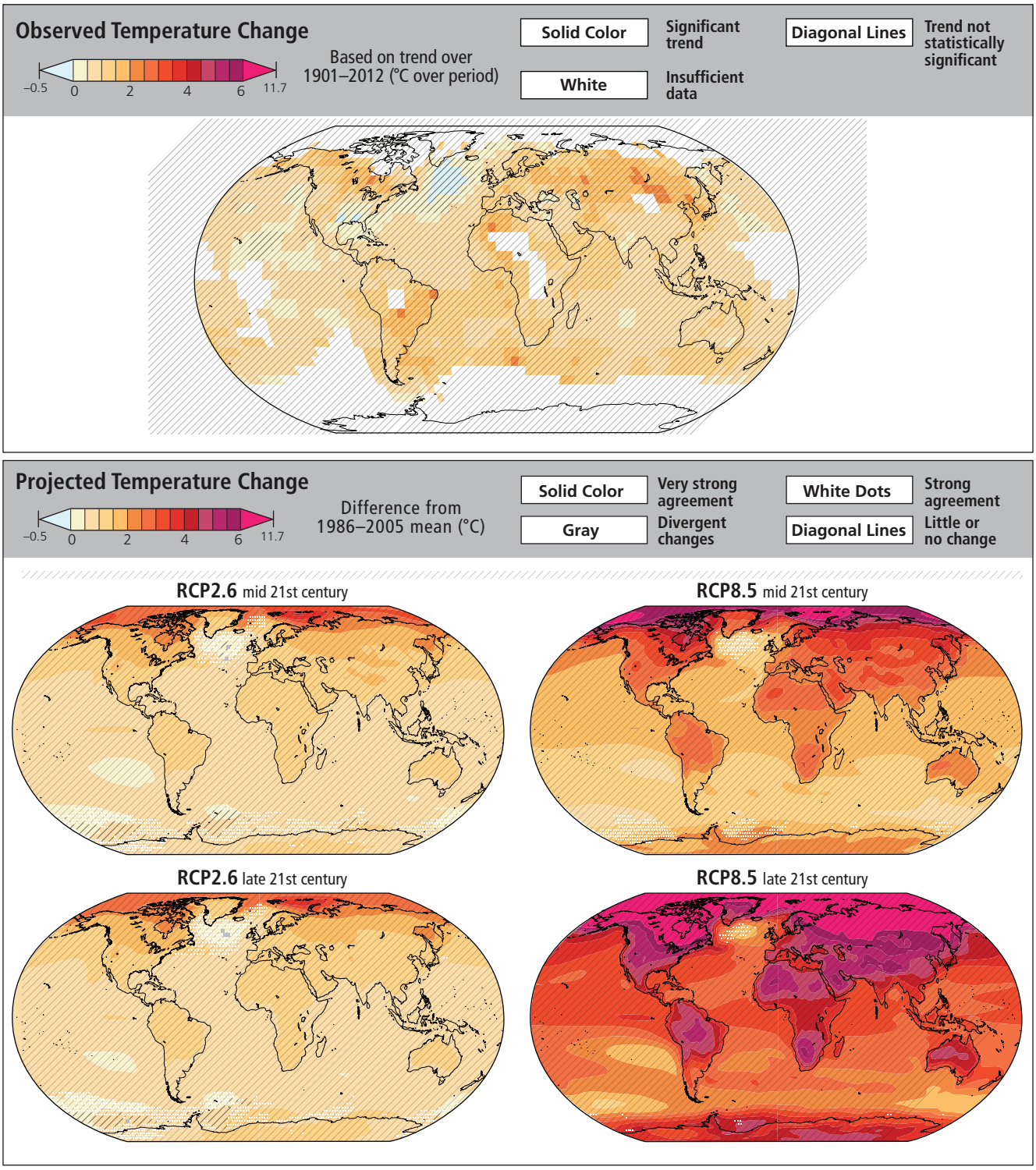

Figure RC-2 | Observed and projected changes in annual average surface temperature. (A) Map of observed annual average temperature change from 1901 to 2012, derived from a linear trend where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period); other areas are white. Solid colors indicate areas where trends are significant at the 10% level (after accounting for autocorrelation effects on significance testing). Diagonal lines indicate areas where trends are not significant. Observed data (range of grid-point values: –0.53 to +2.50°C over period) are from WGI AR5 Figures SPM.1 and 2.21. (B) Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model mean projections of annual average temperature changes for 2046–2065 and 2081–2100 under Representative Concentration Pathway (RCP) 2.6 and 8.5, relative to 1986–2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-year means) and ≥90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where ≥66% of models show change greater than the baseline variability and ≥66% of models agree on sign of change. Gray indicates areas with divergent changes, where ≥66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where <66% of models show change greater than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. Analysis uses model data from WGI AR5 Figure SPM.8, Box 12.1, and Annex I. The range of grid-point values for the multi-model mean is: +0.19 to +4.08°C for mid 21st century of RCP2.6; +0.06 to +3.85°C for late 21st century of RCP2.6; +0.70 to +7.04°C for mid 21st century of RCP8.5; and +1.38 to +11.71°C for late 21st century of RCP8.5.

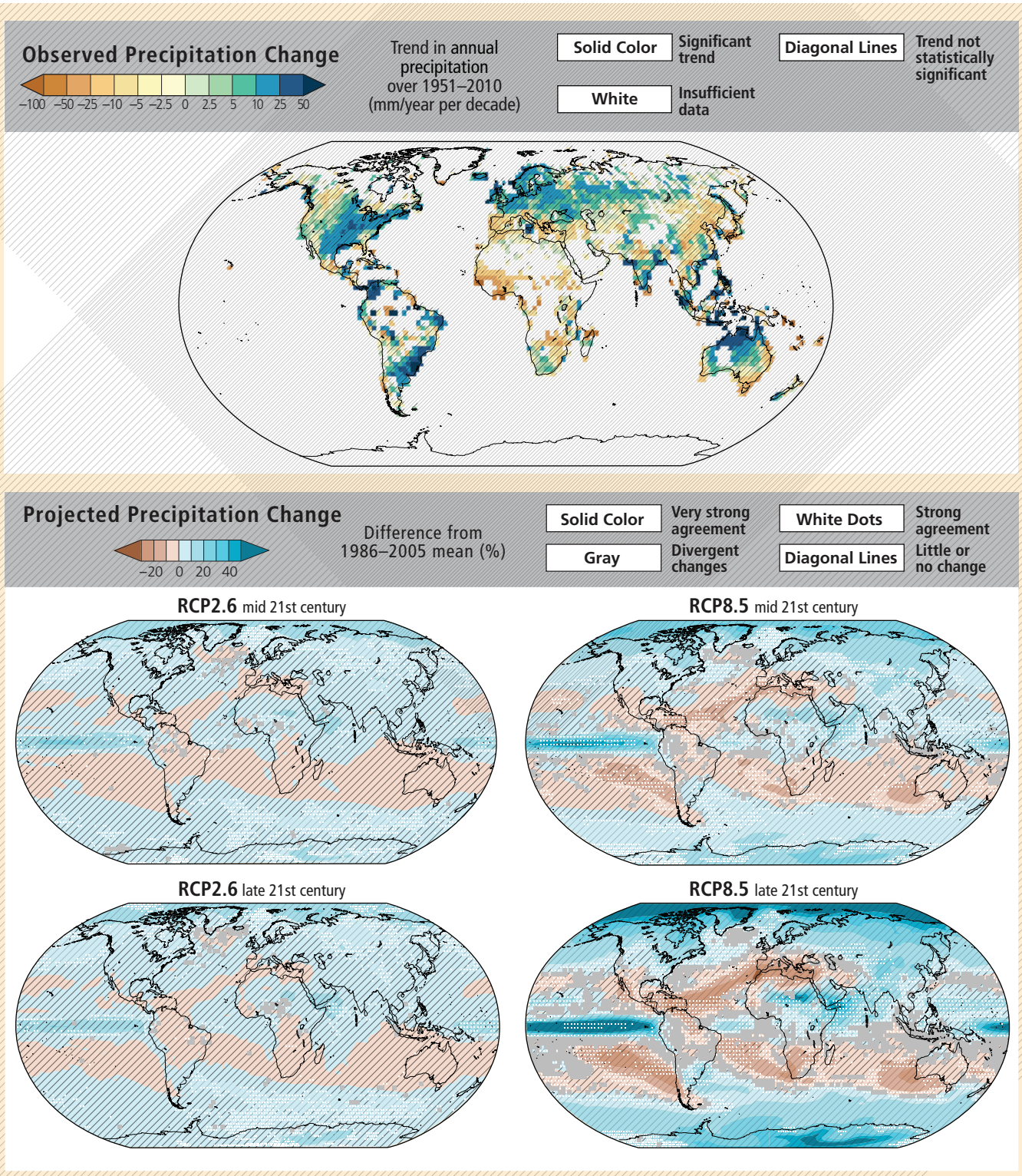

Figure RC-3 | Observed and projected changes in annual average precipitation. (A) Map of observed annual precipitation change from 1951–2010, derived from a linear trend where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period); other areas are white. Solid colors indicate areas where trends are significant at the 10% level (after accounting for autocorrelation effects on significance testing). Diagonal lines indicate areas where trends are not significant. Observed data (range of grid-point values: –185 to +111 mm/year per decade) are from WGI AR5 Figures SPM.2 and 2.29. (B) Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model average percent changes in annual mean precipitation for 2046–2065 and 2081–2100 under Representative Concentration Pathway (RCP) 2.6 and 8.5, relative to 1986–2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-yr means) and ≥90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where ≥66% of models show change greater than the baseline variability and ≥66% of models agree on sign of change. Gray indicates areas with divergent changes, where ≥66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where <66% of models show change greater than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. Analysis uses model data from WGI AR5 Figure SPM.8, Box 12.1, and Annex I. The range of grid-point values for the multi-model mean is: –10 to +24% for mid 21st century of RCP2.6; –9 to +22% for late 21st century of RCP2.6; –19 to +57% for mid 21st century of RCP8.5; and –34 to +112% for late 21st century of RCP8.5.

References

Christensen, J.H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr, and P. Whetton, 2007: Regional climate projections. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 847-940.

IPCC, 2000: *Special Report on Emissions Scenarios* [Nakicenovic, N. and R. Swart (eds.)]. Cambridge University Press, Cambridge, UK, 570 pp.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp.

Knutti, R., R. Furrer, C. Tebaldi, J. Cermak, and G.A. Meehl, 2010: Challenges in combining projections from multiple climate models. *Journal of Climate*, **23(10)**, 2739-2758.

Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Frame, H. Held, E. Kriegler, K.J. Mach, P.R. Matschoss, G.-K. Plattner, G.W. Yohe, and F.W. Zwiers, 2010: *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties*. Intergovernmental Panel on Climate Change (IPCC), www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf.

Meehl, G.A., C. Covey, K.E. Taylor, T. Delworth, R.J. Stouffer, M. Latif, B. McAvaney, and J.F.B. Mitchell, 2007: The WCRP CMIP3 multimodel dataset – a new era in climate change research. *Bulletin of the American Meteorological Society*, **88(9)**, 1383-1394.

Taylor, K.E., R.J. Stouffer, and G.A. Meehl, 2012: An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, **93(4)**, 485-498.

Tebaldi, C., J.M. Arblaster, and Reto Knutti, 2011: Mapping model agreement on future climate projections. *Geophysical Research Letters*, **38(23)**, L23701, doi:10.1029/2011GL049863.

van Vuuren, D.P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S.J. Smith, and S.K. Rose 2011: The representative concentration pathways: an overview. *Climatic Change*, **109(1-2)**, 5-31.

This cross-chapter box should be cited as:

Diffenbaugh, N.S., D.A. Stone, P. Thorne, F. Giorgi, B.C. Hewitson, R.G. Jones, and G.J. van Oldenborgh, 2014: Cross-chapter box on the regional climate summary figures. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 137-141.

RF

Impact of Climate Change on Freshwater Ecosystems due to Altered River Flow Regimes

Petra Döll (Germany), Stuart E. Bunn (Australia)

It is widely acknowledged that the flow regime is a primary determinant of the structure and function of rivers and their associated floodplain wetlands, and flow alteration is considered to be a serious and continuing threat to freshwater ecosystems (Bunn and Arthington, 2002; Poff and Zimmerman, 2010; Poff et al., 2010). Most species distribution models do not consider the effect of changing flow regimes (i.e., changes to the frequency, magnitude, duration, and/or timing of key flow parameters) or they use precipitation as proxy for river flow (Heino et al., 2009).

There is growing evidence that climate change will significantly alter ecologically important attributes of hydrologic regimes in rivers and wetlands, and exacerbate impacts from human water use in developed river basins (*medium confidence*; Xenopoulos et al., 2005; Aldous et al., 2011). By the 2050s, climate change is projected to impact river flow characteristics such as long-term average discharge, seasonality, and statistical high flows (but not statistical low flows) more strongly than dam construction and water withdrawals have done up to around the year 2000 (Figure RF-1; Döll and Zhang, 2010). For one climate scenario (Special Report on Emission Scenarios (SRES) A2 emissions, Met Office Hadley Centre climate prediction model 3 (HadCM3)), 15% of the global land area may be negatively affected, by the 2050s, by a decrease of fish species in the upstream basin of more than 10%, as compared to only 10% of the land area that has already suffered from such decreases due to water withdrawals and dams (Döll and Zhang, 2010). Climate change may exacerbate the negative impacts of dams for freshwater ecosystems but may also provide opportunities for operating dams and power stations to the benefit of riverine ecosystems. This is the case if total runoff increases and, as occurs in Sweden, the annual hydrograph becomes more similar to variation in electricity demand, that is, with a lower spring flood and increased runoff during winter months (Renofalt et al., 2010).

Because biota are often adapted to a certain level of river flow variability, the projected larger variability of river flows that is due to increased climate variability is *likely* to select for generalist or invasive species (Ficke et al., 2007). The relatively stable habitats of groundwater-fed streams in snow-dominated or glacierized basins may be altered by reduced recharge by meltwater and as a result experience more variable (possibly intermittent) flows (Hannah et al., 2007). A high-impact change of flow variability is a flow regime shift from intermittent to perennial or vice versa. It is projected that until the 2050s, river flow regime shifts may occur on 5 to 7% of the global land area, mainly in semiarid areas (Döll and Müller Schmied, 2012; see Table 3-2 in Chapter 3).

In Africa, one third of fish species and one fifth of the endemic fish species occur in eco-regions that may experience a change in discharge or runoff of more than 40% by the 2050s (Thieme et al., 2010). Eco-regions containing more than 80% of Africa's freshwater fish species and several

outstanding ecological and evolutionary phenomena are *likely* to experience hydrologic conditions substantially different from the present, with alterations in long-term average annual river discharge or runoff of more than 10% due to climate change and water use (Thieme et al., 2010).

As a result of increased winter temperatures, freshwater ecosystems in basins with significant snow storage are affected by higher river flows in winter, earlier spring peak flows, and possibly reduced summer low flows (Section 3.2.3). Strongly increased winter peak flows may lead to a decline in salmonid populations in the Pacific Northwest of the USA of 20 to 40% by the 2050s (depending on the climate model) due to scouring of the streambed during egg incubation, the relatively pristine high-elevation areas being affected most (Battin et al., 2007). Reductions in summer low flows will increase the competition for water between ecosystems and irrigation water users (Stewart et al., 2005). Ensuring environmental flows through purchasing or leasing water rights and altering reservoir release patterns will be an important adaptation strategy (Palmer et al., 2009).

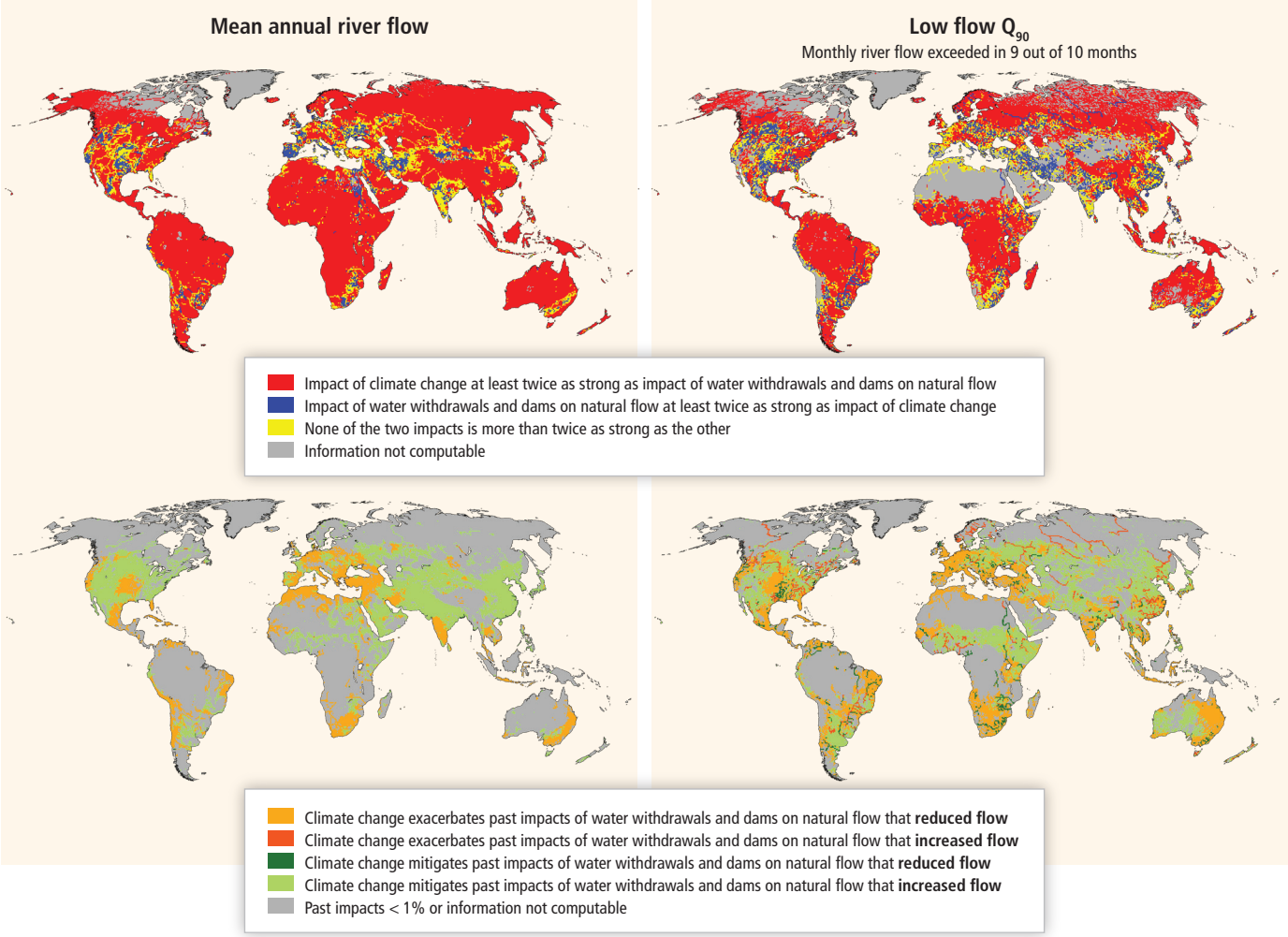

Figure RF-1 | Impact of climate change relative to the impact of water withdrawals and dams on natural flows for two ecologically relevant river flow characteristics (mean annual river flow and monthly low flow Q_{90}), computed by a global water model (Döll and Zhang, 2010). Impact of climate change is the percent change of flow between 1961–1990 and 2041–2070 according to the emissions scenario A2 as implemented by the global climate model Met Office Hadley Centre Coupled Model, version 3 (HadCM3). Impact of water withdrawals and reservoirs is computed by running the model with and without water withdrawals and dams that existed in 2002. Please note that the figure does not reflect spatial differences in the magnitude of change.

Observations and models suggest that global warming impacts on glacier and snow-fed streams and rivers will pass through two contrasting phases (Burkett et al., 2005; Vuille et al., 2008; Jacobsen et al., 2012). In the first phase, when river discharge is increased as a result of intensified melting, the overall diversity and abundance of species may increase. However, changes in water temperature and stream flow may have negative impacts on narrow range endemics (Jacobsen et al., 2012). In the second phase, when snowfields melt early and glaciers have shrunken to the point that late-summer stream flow is reduced, broad negative impacts are foreseen, with species diversity rapidly declining once a critical threshold of roughly 50% glacial cover is crossed (Figure RF-2).

River discharge also influences the response of river temperatures to increases of air temperature. Globally averaged, air temperature increases of 2°C, 4°C, and 6°C are estimated to lead to increases of annual mean river temperatures of 1.3°C, 2.6°C, and 3.8°C, respectively (van Vliet

et al., 2011). Discharge decreases of 20% and 40% are computed to result in additional increases of river water temperature of 0.3° C and 0.8°C on average (van Vliet et al., 2011). Therefore, where rivers will experience drought more frequently in the future, freshwater-dependent biota will suffer not only directly by changed flow conditions but also by drought-induced river temperature increases, as well as by related decreased oxygen and increased pollutant concentrations.

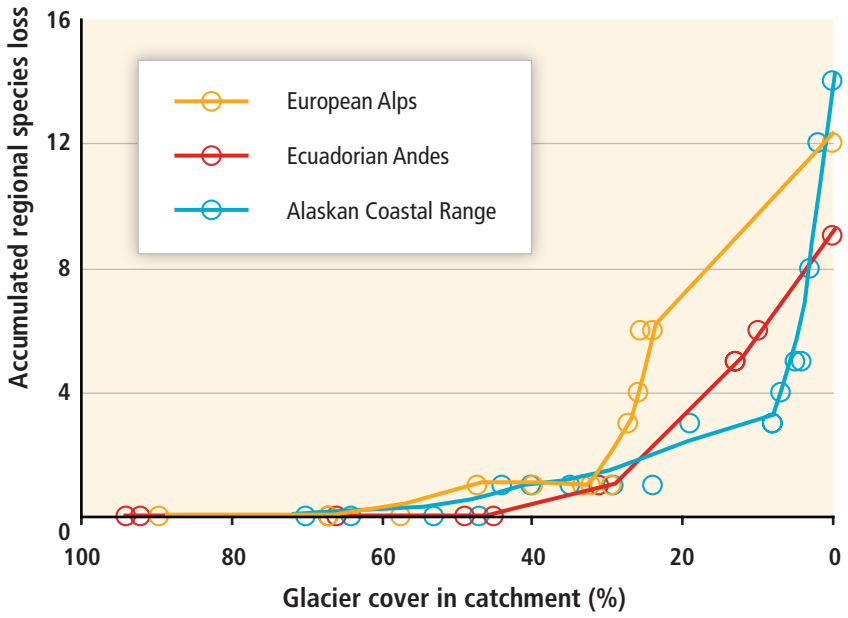

Figure RF-2 | Accumulated loss of regional species richness (gamma diversity) of macroinvertebrates as a function of glacial cover in catchment. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%, and 9 to 14 species are predicted to be lost with the complete disappearance of glaciers in each region, corresponding to 11, 16, and 38% of the total species richness in the three study regions in Ecuador, Europe, and Alaska. Data are derived from multiple river sites from the Ecuadorian Andes and Swiss and Italian Alps, and a temporal study of a river in the Coastal Range Mountains of southeast Alaska over nearly three decades of glacial shrinkage. Each data point represents a river site (Europe or Ecuador) or date (Alaska), and lines are Lowess fits. (Adapted by permission from Jacobsen et al., 2012.)

RF

References

Aldous, A., J. Fitzsimons, B. Richter, and L. Bach, 2011: Droughts, floods and freshwater ecosystems: evaluating climate change impacts and developing adaptation strategies. *Marine and Freshwater Research*, **62(3)**, 223-231.

Battin, J., M.W. Wiley, M.H. Ruckelshaus, R.N. Palmer, E. Korb, K.K. Bartz, and H. Imaki, 2007: Projected impacts of climate change on salmon habitat restoration. *Proceedings of the National Academy of Sciences of the United States of America*, **104(16)**, 6720-6725.

Bunn, S.E. and A.H. Arthington, 2002: Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management*, **30(4)**, 492-507.

Burkett, V., D. Wilcox, R. Stottlemyer, W. Barrow, D. Fagre, J. Baron, J. Price, J. Nielsen, C. Allen, D. Peterson, G. Ruggerone, and T. Doyle, 2005: Nonlinear dynamics in ecosystem response to climatic change: case studies and policy implications. *Ecological Complexity*, **2(4)**, 357-394.

Döll, P. and H. Müller Schmied, 2012: How is the impact of climate change on river flow regimes related to the impact on mean annual runoff? A global-scale analysis. *Environmental Research Letters*, **7(1)**, 014037, doi:10.1088/1748-9326/7/1/014037.

Döll, P. and J. Zhang, 2010: Impact of climate change on freshwater ecosystems: a global-scale analysis of ecologically relevant river flow alterations. *Hydrology and Earth System Sciences*, **14(5)**, 783-799.

Ficke, A.D., C.A. Myrick, and L.J. Hansen, 2007: Potential impacts of global climate change on freshwater fisheries. *Reviews in Fish Biology and Fisheries*, **17(4)**, 581-613.

Hannah, D.M., L.E. Brown, A.M. Milner, A.M. Gurnell, G.R. McGregord, G.E. Petts, B.P.G. Smith, and D.L. Snook, 2007: Integrating climate-hydrology-ecology for alpine river systems. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **17(6)**, 636-656.

Heino, J., R. Virkalla, and H. Toivonen, 2009: Climate change and freshwater biodiversity: detected patterns, future trends and adaptations in northern regions. *Biological Reviews*, **84(1)**, 39-54.

Jacobsen, D., A.M. Milner, L.E. Brown, and O. Dangles, 2012: Biodiversity under threat in glacier-fed river systems. *Nature Climate Change*, **2(5)**, 361-364.

Palmer, M.A., D.P. Lettenmaier, N.L. Poff, S.L. Postel, B. Richter, and R. Warner, 2009: Climate change and river ecosystems: protection and adaptation options. *Environmental Management*, **44(6)**, 1053-1068.

Poff, N.L. and J.K.H. Zimmerman, 2010: Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology*, **55(1)**, 194-205.

Poff, N.L., B.D. Richter, A.H. Arthington, S.E. Bunn, R.J. Naiman, E. Kendy, M. Acreman, C. Apse, B.P. Bledsoe, M.C. Freeman, J. Henriksen, R.B. Jacobson, J.G. Kennen, D.M. Merritt, J.H. O'Keeffe, J.D. Olden, K. Rogers, R.E. Tharme, and A. Warner, 2010: The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology*, **55(1)**, 147-170.

Renofalt, B.M., R. Jansson, and C. Nilsson, 2010: Effects of hydropower generation and opportunities for environmental flow management in Swedish riverine ecosystems. *Freshwater Biology*, **55(1)**, 49-67.

Stewart, I., D. Cayan, and M. Dettinger, 2005: Changes toward earlier streamflow timing across western North America. *Journal of Climate*, **18(8)**, 1136-1155.

Thieme, M.L., B. Lehner, R. Abell, and J. Matthews, 2010: Exposure of Africa's freshwater biodiversity to a changing climate. *Conservation Letters*, **3(5)**, 324-331.

van Vliet, M.T.H., F. Ludwig, J.J.G. Zwolsman, G.P. Weedon, and P. Kabat, 2011: Global river temperatures and sensitivity to atmospheric warming and changes in river flow. *Water Resources Research*, **47(2)**, W02544, doi:10.1029/2010WR009198.

Vuille, M., B. Francou, P. Wagnon, I. Juen, G. Kaser, B.G. Mark, and R.S. Bradley, 2008: Climate change and tropical Andean glaciers: past, present and future. *Earth-Science Reviews*, **89(3-4)**, 79-96.

Xenopoulos, M., D. Lodge, J. Alcamo, M. Marker, K. Schulze, and D. Van Vuuren, 2005: Scenarios of freshwater fish extinctions from climate change and water withdrawal. *Global Change Biology*, **11(10)**, 1557-1564.

This cross-chapter box should be cited as:

Döll, P. and S.E. Bunn, 2014: *Cross-chapter box on the impact of climate change on freshwater ecosystems due to altered river flow regimes. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 143-146.

TC

Building Long-Term Resilience from Tropical Cyclone Disasters

Yoshiki Saito (Japan), Kathleen McInnes (Australia)

Tropical cyclones (also referred to as hurricanes and typhoons in some regions) cause powerful winds, torrential rains, high waves, and storm surge, all of which can have major impacts on society and ecosystems. Bangladesh and India suffer 86% of mortality from tropical cyclones (Murray et al., 2012), which occurs mainly during the rarest and most severe storm categories (i.e., Categories 3, 4, and 5 on the Saffir–Simpson scale).

About 90 tropical cyclones occur globally each year (Seneviratne et al., 2012) although interannual variability is large. Changes in observing techniques, particularly after the introduction of satellites in the late 1970s, confounds the assessment of trends in tropical cyclone frequencies and intensities, which leads to *low confidence* that any observed long-term (i.e., 40 years or more) increases in tropical cyclone activity are robust, after accounting for past changes in observing capability (Seneviratne et al., 2012; Chapter 2). There is also *low confidence* in the detection and attribution of century scale trends in tropical cyclones. Future changes to tropical cyclones arising from climate change are *likely* to vary by region. This is because there is *medium confidence* that for certain regions, shorter-term forcing by natural and anthropogenic aerosols has had a measurable effect on tropical cyclones. Tropical cyclone frequency is *likely* to decrease or remain unchanged over the 21st century, while intensity (i.e., maximum wind speed and rainfall rates) is *likely* to increase (WGI AR5 Section 14.6). Regionally specific projections have *lower confidence* (see WGI AR5 Box 14.2).

Longer-term impacts from tropical cyclones include salinization of coastal soils and water supplies and subsequent food and water security issues from the associated storm surge and waves (Terry and Chui, 2012). However, preparation for extreme tropical cyclone events through improved governance and development to reduce their impacts provides an avenue for building resilience to longer-term changes associated with climate change.

Asian deltas are particularly vulnerable to tropical cyclones owing to their large population density in expanding urban areas (Nicholls et al., 2007). Extreme cyclones in Asia since 1970 caused more than 0.5 million fatalities (Murray et al., 2012), for example, cyclones Bhola in 1970, Gorky in 1991, Thelma in 1998, Gujarat in 1998, Orissa in 1999, Sidr in 2007, and Nargis in 2008. Tropical cyclone Nargis hit Myanmar on May 2, 2008 and caused more than 138,000 fatalities. Several-meter high storm surges widely flooded densely populated coastal areas of the Irrawaddy Delta and surrounding areas (Revenga et al., 2003; Brakenridge et al., 2013). The flooded areas were captured by a NASA Moderate Resolution Imaging Spectrometer (MODIS) image on May 5, 2008 (see Figure TC-1).

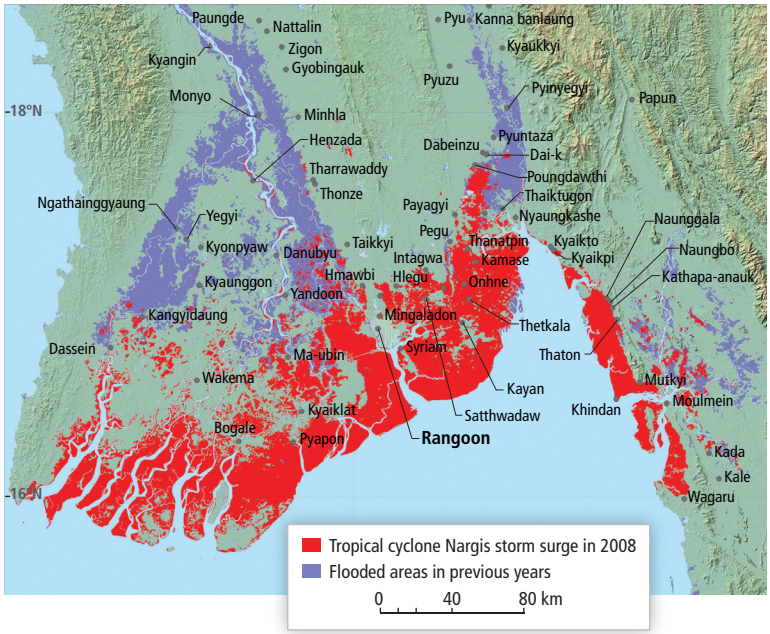

Figure TC-1 | The intersection of inland and storm surge flooding. Red shows May 5, 2008 Moderate Resolution Imaging Spectrometer (MODIS) mapping of the tropical cyclone Nargis storm surge along the Irrawaddy Delta and to the east, Myanmar. The purple areas to the north were flooded by the river in prior years. (Source: Brakenridge et al., 2013.)

Murray et al. (2012) compared the response to cyclone Sidr in Bangladesh in 2007 and Nargis in Myanmar in 2008 and demonstrated how disaster risk reduction methods could be successfully applied to climate change adaptation. Sidr, despite being of similar strength to Nargis, caused far fewer fatalities (3400 compared to more than 138,000) and this was attributed to advancement in preparedness and response in Bangladesh through experience in previous cyclones such as Bhola and Gorky. The responses included the construction of multistoried cyclone shelters, improvement of forecasting and warning capacity, establishing a coastal volunteer network, and coastal reforestation of mangroves. Disaster risk management strategies for tropical cyclones in coastal areas create protective measures, anticipate and plan for extreme events, and increase the resilience of potentially exposed communities. The integration of activities relating to education, training, and awareness-raising into relevant ongoing processes and practices is important for the long-term success of disaster risk reduction and management (Murray et al., 2012). However, Birkmann and Teichman (2010) caution that while the combination of risk reduction and climate change adaptation strategies may be desirable, different spatial and temporal scales, norm systems, and knowledge types and sources between the two goals can confound their effective combination.

TC

References

Birkman, J. and K. von Teichman, 2010: Integrating disaster risk reduction and climate change adaptation: key challenges – scales, knowledge and norms. *Sustainability Science*, **5**, 171-184.

Brakenridge, G.R., J.P.M. Syvitski, I. Overeem, S.A. Higgins, A.J. Kettner, J.A. Stewart-Moore, and R. Westerhoff, 2013: Global mapping of storm surges and the assessment of delta vulnerability. *Natural Hazards*, **66**, 1295-1312, doi:10.1007/s11069-012-0317-z.

Murray V., G. McBean, M. Bhatt, S. Borsch, T.S. Cheong, W.F. Erian, S. Llosa, F. Nadim, M. Nunez, R. Oyun, and A.G. Suarez, 2012: Case studies. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 487-542.

Nicholls, R.J., 2007: *Adaptation Options for Coastal Areas and Infrastructure: An Analysis for 2030*. Report to the United Nations Framework Convention on Climate Change (UNFCCC), UNFCCC Secretariat, Bonn, Germany, 35 pp.

Revenga, C., J. Nackoney, E. Hoshino, Y. Kura, and J. Maidens, 2003: Watersheds of Asia and Oceania: AS 12 Irrawaddy. In: *Water Resources eAtlas: Watersheds of the World*. A collaborative product of the International Union for Conservation of Nature (IUCN), the International Water Management Institute (IWMI), the Ramsar Convention Bureau, and the World Resources Institute (WRI), WRI, Washington, DC, USA, pdf.wri.org/watersheds_2003/as13.pdf.

Seneviratne, S.I., N. Nicholls, D. Easterling, C.M. Goodess, S. Kanae, J. Kossin, Y. Luo, J. Marengo, K. McInnes, M. Rahimi, M. Reichstein, A. Sorteberg, C. Vera, and X. Zhang, 2012: Changes in climate extremes and their impacts on the natural physical environment. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 109-230.

Terry, J. and T.F.M. Chui, 2012: Evaluating the fate of freshwater lenses on atoll islands after eustatic sea level rise and cyclone driven inundation: a modelling approach. *Global and Planetary Change*, **88-89**, 76-84.

This cross-chapter box should be cited as:

Saito, Y. and K.L. McInnes, 2014: Cross-chapter box on building long-term resilience from tropical cyclone disasters. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 147-148.

UP

Uncertain Trends in Major Upwelling Ecosystems

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Upwelling is the vertical transport of cold, dense, nutrient-rich, relatively low-pH and often oxygen-poor waters to the euphotic zone where light is abundant. These conditions trigger high levels of primary production and a high biomass of benthic and pelagic organisms. The driving forces of upwelling include wind stress and the interaction of ocean currents with bottom topography. Upwelling intensity also depends on water column stratification. The major upwelling systems of the planet, the Equatorial Upwelling System (EUS; Section 30.5.2, Figure 30.1A) and the Eastern Boundary Upwelling Ecosystems (EBUE; Section 30.5.5, Figure 30.1A), represent only 10% of the ocean surface but contribute nearly 25% to global fish production (Figure 30.1B, Table SM30.1).

Marine ecosystems associated with upwelling systems can be influenced by a range of "bottom-up" trophic mechanisms, with upwelling, transport, and chlorophyll concentrations showing strong seasonal and interannual couplings and variability. These, in turn, influence trophic transfer up the food chain, affecting zooplankton, foraging fish, seabirds, and marine mammals.

There is considerable speculation as to how upwelling systems might change in a warming and acidifying ocean. Globally, the heat gain of the surface ocean has increased stratification by 4% (WGI Sections 3.2, 3.3, 3.8), which means that more wind energy is needed to bring deep waters to the surface. It is as yet unclear to what extent wind stress can offset the increased stratification, owing to the uncertainty in wind speed trends (WGI Section 3.4.4). In the tropics, observations of reductions in trade winds over several decades contrast more recent evidence indicating their strengthening since the late 1990s (WGI Section 3.4.4). Observations and modeling efforts in fact show diverging trends in coastal upwelling at the eastern boundaries of the Pacific and the Atlantic. Bakun (1990) proposed that the difference in rates of heat gain between land and ocean causes an increase in the pressure gradient, which results in increased alongshore winds and leads to intensified offshore transport of surface water through Ekman pumping and the upwelling of nutrient-rich, cold waters (Figure CC-UP). Some regional records support this hypothesis; others do not. There is considerable variability in warming and cooling trends over the past decades both within and among systems, making it difficult to predict changes in the intensity of all Eastern EBUEs (Section 30.5.5).

Understanding whether upwelling and climate change will impact resident biota in an additive, synergistic, or antagonistic manner is important for projections of how ecological goods and services provided for human society will change. Even though upwellings may prove more resilient to climate change than other ocean ecosystems because of their ability to function under extremely variable conditions (Capone and Hutchins, 2013), consequences of their shifts

are highly relevant because these systems provide a significant portion of global primary productivity and fishery catch (Figure 30.1 A, B; Table SM30.1). Increased upwelling would enhance fisheries yields. However, the export of organic material from surface to deeper layers of the ocean may increase and stimulate its decomposition by microbial activity, thereby enhancing oxygen depletion and CO_2 enrichment in deeper water layers. Once this water returns to the surface through upwelling, benthic and pelagic coastal communities will be exposed to acidified and deoxygenated water which may combine with anthropogenic impact to negatively affect marine biota and ecosystem structure of the upper ocean (*high confidence*; Sections 6.3.2, 6.3.3, 30.3.2.2, 30.3.2.3). Extreme hypoxia may result in abnormal mortalities of fishes and invertebrates (Keller et al., 2010), reduce fisheries' catch potential, and impact aquaculture in coastal areas (Barton et al., 2012; see also Sections 5.4.3.3, 6.3.3, 6.4.1, 30.5.1.1.2, 30.5.5.1.3). Shifts in upwelling also coincide with an apparent increase in the frequency of submarine eruptions of methane and hydrogen sulfide gas, caused by enhanced formation and sinking of phytoplankton biomass to the hypoxic or anoxic sea floor. This combination of factors has been implicated in the extensive mortality of coastal fishes and invertebrates (Bakun and Weeks, 2004; Bakun et al., 2010), resulting in significant reductions in fishing productivity, such as Cape hake (*Merluccius capensis*), Namibia's most valuable fishery (Hamukuaya et al., 1998).

Reduced upwelling would also reduce the productivity of important pelagic fisheries, such as for sardines, anchovies and mackerel, with major consequences for the economies of several countries (Section 6.4.1, Chapter 7, Figure 30.1A, B, Table S30.1). However, under projected scenarios of reduced upward supply of nutrients due to stratification of the open ocean, upwelling of both nutrients and trace elements may become increasingly important to maintaining upper ocean nutrient and trace metal inventories. It has been suggested that upwelling areas may also increase nutrient content and productivity under enhanced stratification, and that upwelled and partially denitrified waters containing excess phosphate may select for N_2-fixing microorganisms (Deutsch et al., 2007; Deutsch and Weber, 2012), but field observations of N_2 fixation in these regions have not supported these predictions (Fernandez et al., 2011; Franz et al., 2012). The role of this process in global primary production thus needs to be validated (*low confidence*).

The central question therefore is whether or not upwelling will intensify, and if so, whether the effects of intensified upwelling on O_2 and CO_2 inventories will outweigh its benefits for primary production and associated fisheries and aquaculture (*low confidence*). In any case increasing atmospheric CO_2 concentrations will equilibrate with upwelling waters that may cause them to become more corrosive, depending on pCO_2 of the upwelled water, and potentially increasingly impact the biota of EBUEs.

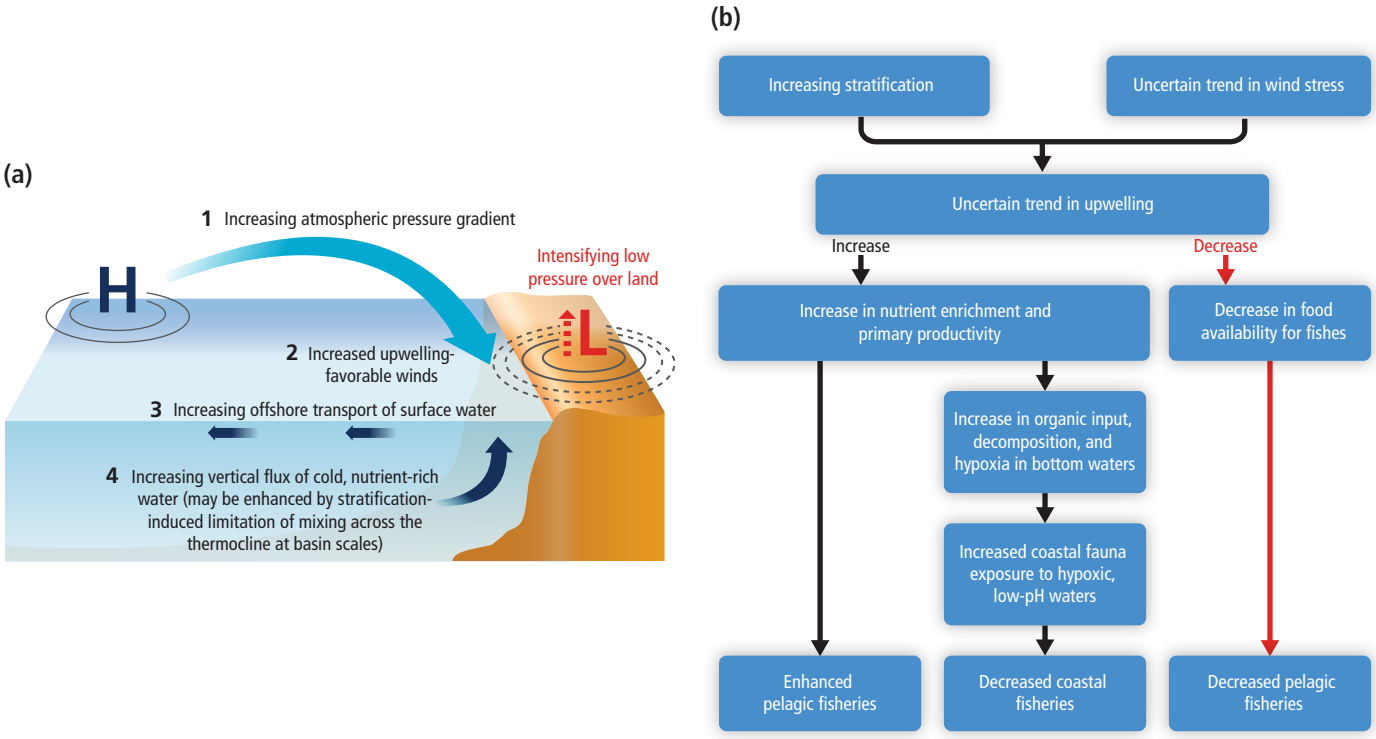

Figure UP-1 | (a) Hypothetic mechanism of increasing coastal wind–driven upwelling at Equatorial and Eastern Boundary upwelling systems (EUS, EBUE, Figure 30-1), where differential warming rates between land and ocean results in increased land–ocean (1) pressure gradients that produce (2) stronger alongshore winds and (3) offshore movement of surface water through Ekman transport, and (4) increased upwelling of deep cold nutrient rich waters to replace it. (b) Potential consequences of climate change in upwelling systems. Increasing stratification and uncertainty in wind stress trends result in uncertain trends in upwelling. Increasing upwelling may result in higher input of nutrients to the euphotic zone, and increased primary production, which in turn may enhance pelagic fisheries, but also decrease coastal fisheries due to an increased exposure of coastal fauna to hypoxic, low pH waters. Decreased upwelling may result in lower primary production in these systems with direct impacts on pelagic fisheries productivity.

References

Bakun, A., 1990: Global climate change and intensification of coastal ocean upwelling. *Science*, **247(4939)**, 198-201.

Bakun, A. and S.J. Weeks, 2004: Greenhouse gas buildup, sardines, submarine eruptions and the possibility of abrupt degradation of intense marine upwelling ecosystems. *Ecology Letters*, **7(11)**, 1015-1023.

Bakun, A., D. B. Field, A. N. A. Redondo-Rodriguez, and S. J. Weeks, 2010: Greenhouse gas, upwelling-favorable winds, and the future of coastal ocean upwelling ecosystems. *Global Change Biology* **16**:1213-1228.

Barton, A., B. Hales, G.G. Waldbusser, C. Langdon, and R.A. Feely, 2012: The Pacific oyster, *Crassostrea gigas*, shows negative correlation to naturally elevated carbon dioxide levels: implications for near-term ocean acidification effects. *Limnology and Oceanography*, **57(3)**, 698-710.

Capone, D.G. and D.A. Hutchins, 2013: Microbial biogeochemistry of coastal upwelling regimes in a changing ocean. *Nature Geoscience*, **6**(**9**) 711-717.

Deutsch, C. and T. Weber, 2012: Nutrient ratios as a tracer and driver of ocean biogeochemistry. *Annual Review of Marine Science*, **4**, 113-141.

Deutsch, C., J.L. Sarmiento, D.M. Sigman, N. Gruber, and J.P. Dunne, 2007: Spatial coupling of nitrogen inputs and losses in the ocean. *Nature*, **445(7124)**, 163-167.

Fernandez, C., L. Farías, and O. Ulloa, 2011: Nitrogen fixation in denitrified marine waters. *PLoS ONE*, **6(6)**, e20539, doi:10.1371/journal.pone.0020539.

Franz, J., G. Krahmann, G. Lavik, P. Grasse, T. Dittmar, and U. Riebesell, 2012: Dynamics and stoichiometry of nutrients and phytoplankton in waters influenced by the oxygen minimum zone in the eastern tropical Pacific. *Deep-Sea Research Part I: Oceanographic Research Papers*, **62**, 20-31.

Hamukuaya, H., M.J. O'Toole, and P.M.J. Woodhead, 1998: Observations of severe hypoxia and offshore displacement of Cape hake over the Namibian shelf in 1994. *South African Journal of Marine Science*, **19(1)**, 57-59.

Keller, A.A., V. Simon, F. Chan, W.W. Wakefield, M.E. Clarke, J.A. Barth, D. Kamikawa and E.L. Fruh, 2010: Demersal fish and invertebrate biomass in relation to an offshore hypoxic zone along the US West Coast. *Fisheries Oceanography*, **19**, 76-87.

This cross-chapter box should be cited as:

Lluch-Cota, S.E., O. Hoegh-Guldberg, D. Karl, H.-O. Pörtner, S. Sundby, and J.-P. Gattuso, 2014: *Cross-chapter box on uncertain trends in major upwelling ecosystems. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 149-151.

UR

Urban–Rural Interactions – Context for Climate Change Vulnerability, Impacts, and Adaptation

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Rural areas and urban areas have always been interconnected and interdependent, but recent decades have seen new forms of these interconnections: a tendency for rural–urban boundaries to become less well defined, and new types of land use and economic activity on those boundaries. These conditions have important implications for understanding climate change impacts, vulnerabilities, and opportunities for adaptation. This box examines three critical implications of these interactions:

1) Climate extremes in rural areas resulting in urban impacts— teleconnections of resources and migration streams mean that climate extremes in non-urban locations with associated shifts in water supply, rural agricultural potential, and the habitability of rural areas will have downstream impacts in cities.
2) Events specific to the rural–urban interface— given the highly integrated nature of rural–urban interface areas and overarching demand to accommodate both rural and urban demands in these settings, there is a set of impacts, vulnerabilities, and opportunities for adaptation specific to these locations. These impacts include loss of local agricultural production, economic marginalization resulting from being neither rural or urban, and stress on human health.
3) Integrated infrastructure and service disruption—as urban demands often take preference, interdependent rural and urban resource systems place nearby rural areas at risk, because during conditions of climate stress, rural areas more often suffer resource shortages or other disruptions to sustain resources to cities. For example, under conditions of resource stress associated with climate risk (e.g., droughts) urban areas are at an advantage because of political, social, and economic requirements to maintain service supply to cities to the detriment of relatively marginal rural sites and settlements.

Urban areas historically have been dependent on the lands just beyond their boundaries for most of their critical resources including water, food, and energy. Although in many contexts, the connections between urban settlements and surrounding rural areas are still present, long distance, teleconnected, large-scale supply chains have been developed particularly with respect to energy resources and food supply (Güneralp et al., 2013). Extreme event disruptions in distant resource areas or to the supply chain and relevant infrastructure can negatively impact the urban areas dependent on these materials (Wilbanks et al., 2012). During the summer of 2012, for instance, an extended drought period in the central United States led to significantly reduced river levels on the Mississippi River that led to interruptions of barge traffic and delay of commodity flows to cities throughout the country. Urban water supply is also vulnerable to droughts in predominantly rural areas. In the case of Bulawayo, Zimbabwe, periodic urban water shortages over the last few decades have been triggered by rural droughts (Mkandla et al., 2005).

A further teleconnection between rural and urban areas is rural–urban migration. There have been cases where migration and urbanization patterns have been to attributed to climate change or its proxies such as in parts of Africa (Morton, 1989; Barrios et al., 2006). However, as recognized by Black et al. (2011), life in rural areas across the world typically involves complex patterns of rural–urban and rural–rural migration, subject to economic, political, social, and demographic drivers, patterns that are modified or exacerbated by climate events and trends rather than solely caused by them.

Globally, an increased blending of urban and rural qualities has occurred. Simon et al. (2006, p. 4) assert that the simple dichotomy between "rural" and "urban" has "long ceased to have much meaning in practice or for policy-making purposes in many parts of the global South." One approach to reconciling this is through the increasing application of the concept of "peri-urban areas" (Simon et al., 2006; Simon, 2008). These areas can be seen as rural locations that have "become more urban in character" (Webster, 2002, p. 5); as sites where households pursue a wider range of income-generating activities while still residing in what appear to be "largely rural landscapes" (Learner and Eakin, 2010, p. 1); or as locations in which rural and urban land uses coexist, whether in contiguous or fragmented units (Bowyer-Bower, 2006). The inhabitants of "core" urban areas within cities have also increasingly turned to agriculture, with production of staple foods, higher value crops and livestock (Bryld, 2003; Devendra et al., 2005; Lerner and Eakin, 2010; Lerner et al., 2013). Bryld (2003) sees this as driven by rural–urban migration and by structural adjustment (e.g., withdrawal of food price controls and food subsidies). Lerner and Eakin (2011; also Lerner et al., 2013) explored reasons why people produce food in urban environments, despite high opportunity costs of land and labor: buffering of risk from insecure urban labor markets; response to consumer demand; and the meeting of cultural needs.

Livelihoods and areas on the rural–urban interface suffer highly specific forms of vulnerability to disasters, including climate-related disasters. These may be summarized as specifically combining urban vulnerabilities of population concentration, dependence on infrastructure, and social diversity limiting social support with rural traits of distance, isolation, and invisibility to policymakers (Pelling and Mustafa, 2010). Increased connectivity can also encourage land expropriation to enable commercial land development (Pelling and Mustafa, 2010). Vulnerability may arise from the coexistence of rural and urban perspectives, which may give rise to conflicts between different social/interest groups and economic activities (Masuda and Garvin, 2008; Solona-Solona 2010; Darly and Torre, 2013).

Additional vulnerability of peri-urban areas is on account of the re-constituted institutional arrangements and their structural constraints (Iaquinta and Drescher, 2000). Rapid declines in traditional informal institutions and forms of collective action, and their imperfect replacement with formal state and market institutions, may also increase vulnerability (Pelling and Mustafa, 2010).

Peri-urban areas and livelihoods have low visibility to policymakers at both local and national levels, and may suffer from a lack of necessary services and inappropriate and uncoordinated policies. In Tanzania and Malawi, national policies of agricultural extension to farmer groups, for example, do not reach peri-urban farmers (Liwenga et al., 2012). In peri-urban areas around Mexico City (Eakin et al., 2013), management of the substantial risk of flooding is led *de facto* by agricultural and water agencies, in the absence of capacity within peri-urban municipalities and despite clear evidence that urban encroachment is a key driver of flood risk. In developed country contexts, suburban–exurban fringe areas often are overlooked in the policy arena that traditionally focuses on rural development and agricultural production, or urban growth and services (Hanlon et al., 2010). The environmental function of urban agriculture, in particular, in protection against flooding, will increase in the context of climate change (Aubry et al., 2012).

However, peri-urban areas and mixed livelihoods more generally on rural–urban interfaces, also exhibit specific factors that increase their resilience to climate shocks (Pelling and Mustafa, 2010). Increased transport connectivity in peri-urban areas can reduce disaster risk by providing a greater diversity of livelihood options and improving access to education. The expansion of local labor markets and wage labor in these areas can strengthen adaptive capacity through providing new livelihood opportunities (Pelling and Mustafa, 2010). Maintaining mixed portfolios of agricultural and non-agricultural livelihoods also spreads risk (Lerner et al., 2013).

In high-income countries, practices attempting to enhance the ecosystem services and localized agriculture more typically associated with lower density areas have been encouraged. In many situations these practices are focused increasingly on climate adaptation and mitigating the impacts of climate extremes such as those associated with heating and the urban heat island effect, or wetland restoration efforts to limit the impact of storm surge wave action (Verburg et al., 2012).

The dramatic growth of urban areas also implies that rural areas and communities are increasingly politically and economically marginalized within national contexts, resulting in potential infrastructure and service disruptions for such sites. Existing rural–urban conflicts for the management of natural resources (Castro and Nielsen, 2003) such as water (Celio et al., 2011) or land use conversion in rural areas, for example, wind farms in rural Catalonia (Zografos and Martínez-Alier, 2009); industrial coastal areas in Sweden (Stepanova and Bruckmeier, 2013); or conversion of rice land into industrial, residential, and recreational uses in the Philippines (Kelly, 1998) have been documented, and it is expected that stress from climate change impacts on land and natural resources will exacerbate these tensions. For instance, climate-induced reductions in water availability may be more of a concern than population growth or increased per capita use for securing continued supplies of water to large cities (Jenerette and Larsen, 2006), which requires an innovative approach to address such conflicts (Pearson et al., 2010).

References

Aubry, C., J. Ramamonjisoa, M.-H. Dabat, J. Rakotoarisoa, J. Rakotondraibe, and L. Rabeharisoa, 2012: Urban agriculture and land use in cities: an approach with the multi-functionality and sustainability concepts in the case of Antananarivo (Madagascar). *Land Use Policy*, **29**, 429-439.

Barrios, S., L. Bertinelli, and E. Strobl, 2006: Climatic change and rural-urban migration: the case of sub-Saharan Africa. *Journal of Urban Economics*, **60**, 357-371.

Black, R., W.N. Adger, N.W. Arnell, S. Dercon, A. Geddes, and D. Thomas, 2011: The effect of environmental change on human migration. *Global Environmental Change*, **21(Suppl. 1)**, S3-S11.

Bowyer-Bower, T., 2006: The inevitable illusiveness of 'sustainability' in the peri-urban interface: the case of Harare. In: *The Peri-Urban Interface: Approaches to Sustainable Natural and Human Resource Use* [McGregor, D., D. Simon, and D. Thompson (eds.)]. Earthscan, London, UK and Sterling, VA, USA, pp. 151-164.

Bryld, E., 2003: Potentials, problems, and policy implications for urban agriculture in developing countries. *Agriculture and Human Values*, **20**, 79-86.

Castro, A.P. and E. Nielsen, 2003: *Natural Resource Conflict Management Case Studies: An Analysis of Power, Participation and Protected Areas*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 268 pp.

Darly, S. and A. Torre, 2013: Conflicts over farmland uses and the dynamics of "agri-urban" localities in the Greater Paris Region: an empirical analysis based on daily regional press and field interviews. *Land Use Policy*, **30**, 90-99.

Devendra, C., J. Morton, B. Rischowsky, and D. Thomas, 2005: Livestock systems. In: *Livestock and Wealth Creation: Improving the Husbandry of Livestock Kept by the Poor in Developing Countries* [Owen, E., A. Kitalyi, N. Jayasuriya, and T. Smith (eds.)]. Nottingham University Press, Nottingham, UK, pp. 29-52.

Dixon, J.M., K.J. Donati, L.L. Pike, and L. Hattersley, 2009: Functional foods and urban agriculture: two responses to climate change-related food insecurity. *New South Wales Public Health Bulletin*, **20(2)**, 14-18.

Eakin, H., A. Lerner, and F. Murtinho, 2013: Adaptive capacity in evolving peri-urban spaces; responses to flood risk in the Upper Lerma River Valley, Mexico. *Global Environmental Change*, **20(1)**, 14-22.

Güneralp, B., K.C. Seto, and M. Ramachandran, 2013: Evidence of urban land teleconnections and impacts on hinterlands. *Current Opinion in Environmental Sustainability*, **5(5)**, 445-451.

Hanlon, B., J.R. Short, and T.J. Vicino, 2010: *Cities and Suburbs: New Metropolitan Realities in the US*. Routledge, Oxford, UK and New York, NY, USA, 304 pp.

Hoggart, K., 2005: *The City's Hinterland: Dynamism and Divergence in Europe's Peri-Urban Territories*. Ashgate Publishing, Ltd., Aldershot, UK and Ashgate Publishing Co., Burlington, VT, USA, 186 pp.

Iaquinta, D.L. and A.W. Drescher, 2000: Defining the peri-urban: rural-urban linkages and institutional connections. *Land Reform: Land Settlement and Cooperatives*, **2000(2)**, 8-26, www.fao.org/docrep/003/X8050T/X8050T00.HTM.

Jenerette, GD and L Larsen, 2006: A global perspective on changing sustainable urban water supplies. *Global and Planetary Change*, **50(3-4)**, 202-211.

Kelly, P.F., 1998: The politics of urban-rural relations: land use conversion in the Philippines. *Environment and Urbanization*, **10(1)**, 35-54, doi:10.1177/095624789801000116.

Lerner, A.M. and H. Eakin, 2010: An obsolete dichotomy? Rethinking the rural-urban interface in terms of food security and production in the global south. *Geographical Journal*, **177(4)**, 311-320.

Lerner, A.M., H. Eakin, and S. Sweeney, 2013: Understanding peri-urban maize production through an examination of household livelihoods in the Toluca Metropolitan Area, Mexico. *Journal of Rural Studies*, **30**, 52-63.

Liwenga, E., E. Swai, L. Nsemwa, A. Katunzi, B. Gwambene, M. Joshua, F. Chipungu, T. Stathers, and R. Lamboll, 2012: *Exploring Urban Rural Interdependence and the Impact of Climate Change in Tanzania and Malawi: Final Narrative Report*. Project Report, International Development Research Centre (IDRC), Ottawa, ON, Canada.

Masuda, J. and T. Garvin, 2008: Whose heartland? The politics of place at the rural-urban interface. *Journal of Rural Studies*, **24**, 118-123.

Mattia, C., C.A. Scott, and M. Giordano, 2010: Urban-agricultural water appropriation: the Hyderabad, India case. *Geographical Journal*, **176(1)**, 39-57.

Mkandla, N., P. Van der Zaag, and P. Sibanda, 2005: Bulawayo water supplies: sustainable alternatives for the next decade. *Physics and Chemistry of the Earth, Parts A/B/C*, **30(11-16)**, 935-942.

Morton, J., 1989: Ethnicity and politics in Red Sea Province, Sudan. *African Affairs*, **88(350)**, 63-76.

Pearson, L.J., A. Coggan, W. Proctor, and T.F. Smith, 2010: A sustainable decision support framework for urban water management. *Water Resources Management*, **24(2)**, 363-376.

Pelling, M. and D. Mustafa, 2010: *Vulnerability, Disasters and Poverty in Desakota Systems*. Political and Development Working Paper Series, No. 31, King's College London, London, UK, 26 pp.

Simon, D., 2008: Urban environments: issues on the peri-urban fringe. *Annual Review of Environmental Resources*, **33**, 167-185.

Simon, D., D. McGregor, and D. Thompson, 2006: Contemporary perspectives on the peri-urban zones of cities in developing countries. In: *The Peri-Urban Interface: Approaches to Sustainable Natural and Human Resource Use* [McGregor, D., D. Simon, and D. Thompson (eds.)]. Earthscan, London, UK and Sterling, VA, USA, pp. 3-17.

Solana-Solana, M., 2010: Rural gentrification in Catalonia, Spain: a case study of migration, social change and conflicts in the Empordanet area. *Geoforum*, **41(3)**, 508-517.

Stepanova, O. and K. Bruckmeier, 2013: Resource use conflicts and urban-rural resource use dynamics in Swedish coastal landscapes: comparison and synthesis. *Journal of Environmental Policy & Planning*, **15(4)**, 467-492, doi:10.1080/1523908X.2013.778173.

Verburg, P.H., E. Koomen, M. Hilferink, M. Perez-Soba, and J.P. Lesschen, 2012: An assessment of the impact of climate adaptation measures to reduce flood risk on ecosystem services. *Landscape Ecology*, **27**, 473-486.

Webster, D., 2002: *On the Edge: Shaping the Future of Peri-Urban East Asia*. Asia/Pacific Research Center (A/PARC), Stanford, CA, USA, 49 pp.

Wilbanks, T., S. Fernandez, G. Backus, P. Garcia, K. Jonietz, P. Kirshen, M. Savonis, W. Solecki, and T. Toole, 2012: *Climate Change and Infrastructure, Urban systems and Vulnerabilities*. Technical Report prepared by the Oak Ridge National Laboratory (ORNL) for the US Department of Energy in support of the National Climate Assessment, ORNL, Oak Ridge, TN, 19 pp., www.esd.ornl.gov/eess/Infrastructure.pdf.

Zasada, I., 2011: Multifunctional peri-urban agriculture – a review of societal demands and the provision of goods and services by farming. *Land Use Policy*, **28(4)**, 639-648.

Zografos, C. and J. Martínez-Alier, 2009: The politics of landscape value: a case study of wind farm conflict in rural Catalonia. *Environment and Planning A*, **41(7)**, 1726-1744.

This cross-chapter box should be cited as:

Morton, J.F., W. Solecki, P. Dasgupta, D. Dodman, and M.G. Rivera-Ferre, 2014: Cross-chapter box on urban–rural interactions—context for climate change vulnerability, impacts, and adaptation. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 153-155.

VW

Active Role of Vegetation in Altering Water Flows under Climate Change

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Climate, vegetation, and carbon and water cycles are intimately coupled, in particular via the simultaneous transpiration and CO_2 uptake through plant stomata in the process of photosynthesis. Hence, water flows such as runoff and evapotranspiration are affected not only directly by anthropogenic climate change as such (i.e., by changes in climate variables such as temperature and precipitation), but also indirectly by plant responses to increased atmospheric CO_2 concentrations. In addition, effects of climate change (e.g., higher temperature or altered precipitation) on vegetation structure, biomass production, and plant distribution have an indirect influence on water flows. Rising CO_2 concentration affects vegetation and associated water flows in two contrasting ways, as suggested by ample evidence from Free Air CO_2 Enrichment (FACE), laboratory and modeling experiments (e.g., Leakey et al., 2009; Reddy et al., 2010; de Boer et al., 2011). On the one hand, a *physiological* effect leads to reduced opening of stomatal apertures, which is associated with lower water flow through the stomata, that is, lower leaf-level transpiration. On the other hand, a *structural* effect ("fertilization effect") stimulates photosynthesis and biomass production of C_3 plants including all tree species, which eventually leads to higher transpiration at regional scales. A key question is to what extent the climate- and CO_2-induced changes in vegetation and transpiration translate into changes in regional and global runoff.

The physiological effect of CO_2 is associated with an increased intrinsic water use efficiency (WUE) of plants, which means that less water is transpired per unit of carbon assimilated. Records of stable carbon isotopes in woody plants (Peñuelas et al., 2011) verify this finding, suggesting an increase in WUE of mature trees by 20.5% between the early 1960s and the early 2000s. Increases since pre-industrial times have also been found for several forest sites (Andreu-Hayles et al., 2011; Gagen et al., 2011; Loader et al., 2011; Nock et al., 2011) and in a temperate semi-natural grassland (Koehler et al., 2010), although in one boreal tree species WUE ceased to increase after 1970 (Gagen et al., 2011). Analysis of long-term whole-ecosystem carbon and water flux measurements from 21 sites in North American temperate and boreal forests corroborates a notable increase in WUE over the two past decades (Keenan et al., 2013). An increase in global WUE over the past century is supported by ecosystem model results (Ito and Inatomi, 2012).

A key influence on the significance of increased WUE for large-scale transpiration is whether vegetation structure and production has remained approximately constant (as assumed in the global modeling study by Gedney et al., 2006) or has increased in some regions due to the structural CO_2 effect (as assumed in models by Piao et al., 2007; Gerten et al., 2008). While field-based results vary considerably among sites, tree ring studies suggest that tree growth did not increase globally since the 1970s in response to climate and CO_2 change (Andreu-Hayles et al.,

2011; Peñuelas et al., 2011). However, basal area measurements at more than 150 plots across the tropics suggest that biomass and growth rates in intact tropical forests have increased in recent decades (Lewis et al., 2009). This is also confirmed for 55 temperate forest plots, with a suspected contribution of CO_2 effects (McMahon et al., 2010). Satellite observations analyzed in Donohue et al. (2013) suggest that an increase in vegetation cover by 11% in warm drylands (1982–2010 period) is attributable to CO_2 fertilization. Owing to the interplay of physiological and structural effects, the net impact of CO_2 increase on global-scale transpiration and runoff remains rather poorly constrained. This is also true because nutrient limitation, often omitted in modeling studies, can suppress the CO_2 fertilization effect (see Rosenthal and Tomeo, 2013).

Therefore, there are conflicting views on whether the direct CO_2 effects on plants already have a significant influence on evapotranspiration and runoff at global scale. AR4 reported work by Gedney et al. (2006) that suggested that the physiological CO_2 effect (lower transpiration) contributed to a supposed increase in global runoff seen in reconstructions by Labat et al. (2004). However, a more recent analysis based on a more complete data set (Dai et al., 2009) suggested that river basins with decreasing runoff outnumber basins with increasing runoff, such that a small decline in global runoff is *likely* for the period 1948–2004. Hence, detection of vegetation contributions to changes in water flows critically depends on the availability and quality of hydrometeorological observations (Haddeland et al., 2011; Lorenz and Kunstmann, 2012). Overall, the evidence since AR4 suggests that climatic variations and trends have been the main driver of global runoff change in the past decades; both CO_2 increase and land use change have contributed less (Piao et al., 2007; Gerten et al., 2008; Alkama et al., 2011; Sterling et al., 2013). Oliveira et al. (2011) furthermore pointed to the importance of changes in incident solar radiation and the mediating role of vegetation; according to their global simulations, a higher diffuse radiation fraction during 1960–1990 may have increased evapotranspiration in the tropics by 3% due to higher photosynthesis from shaded leaves.

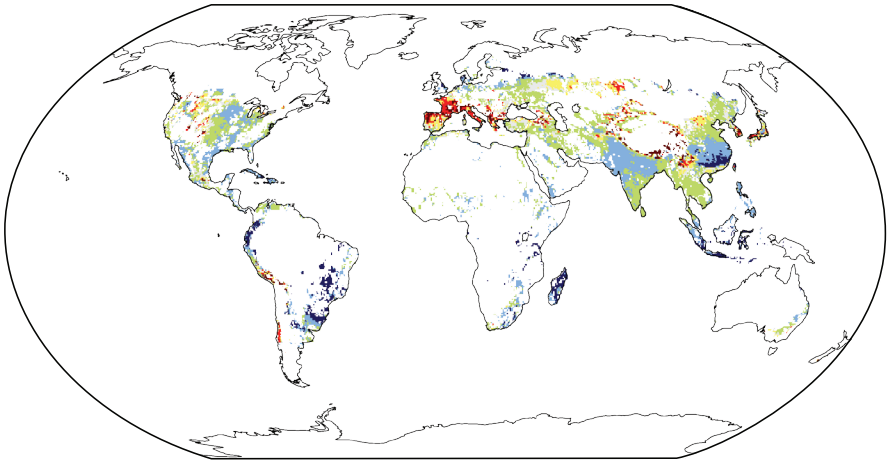
It is uncertain how vegetation responses to future increases in CO_2 and to climate change will modulate the impacts of climate change on freshwater flows. Twenty-first century continental- and basin-scale runoff is projected by some models to either increase more or decrease less when the physiological CO_2 effect is included in addition to climate change effects (Betts et al., 2007; Murray et al., 2012). This could somewhat ease the increase in water scarcity anticipated in response to future climate change and population growth (Gerten et al., 2011; Wiltshire et al., 2013). In absolute terms, the isolated effect of CO_2 has been modeled to increase future global runoff by 4 to 5% (Gerten et al., 2008) up to 13% (Nugent and Matthews, 2012) compared to the present, depending on the assumed CO_2 trajectory and whether feedbacks of changes in vegetation structure and distribution to the atmosphere are accounted for (they were in Nugent and Matthews, 2012). In a global model intercomparison study (Davie et al., 2013), two out of four models projected stronger increases and, respectively, weaker decreases in runoff when considering CO_2 effects compared to simulations with constant CO_2 concentration (consistent with the above findings, though magnitudes differed between the models), but two other models showed the reverse. Thus, the choice of models and the way they represent the coupling between CO_2, stomatal closure, and plant growth is a source of uncertainty, as also suggested by Cao et al. (2009). Lower transpiration due to rising CO_2 concentration may also affect future regional climate change itself (Boucher et al., 2009) and enhance the contrast between land and ocean surface warming (Joshi et al., 2008). Overall, although physiological and structural effects will influence water flows in many regions, precipitation and temperature effects are *likely* to remain the prime influence on global runoff (Alkama et al., 2010).

An application of a soil–vegetation–atmosphere–transfer model indicates complex responses of groundwater recharge to vegetation-mediated changes in climate, with computed groundwater recharge being always larger than would be expected from just accounting for changes in rainfall (McCallum et al., 2010). Another study found that even if precipitation slightly decreased, groundwater recharge might increase as a net effect of vegetation responses to climate change and CO_2 rise, that is, increasing WUE and either increasing or decreasing leaf area (Crosbie et al., 2010). Depending on the type of grass in Australia, the same change in climate is suggested to lead to either increasing or decreasing groundwater recharge in this location (Green et al., 2007). For a site in the Netherlands, a biomass decrease was computed for each of eight climate scenarios indicating drier summers and wetter winters (A2 emissions scenario), using a fully coupled vegetation and variably saturated hydrological model. The resulting increase in groundwater recharge up-slope was simulated to lead to higher water tables and an extended habitat for down-slope moisture-adapted vegetation (Brolsma et al., 2010).

Using a large ensemble of climate change projections, Konzmann et al. (2013) put hydrological changes into an agricultural perspective and suggested that the net result of physiological and structural CO_2 effects on crop irrigation requirements would be a global reduction (Figure VW-1). Thus, adverse climate change impacts on irrigation requirements and crop yields might be partly buffered as WUE and crop production improve (Fader et al., 2010). However, substantial CO_2-driven improvements will be realized only if proper management abates limitation of plant growth by nutrient availability or other factors.

Changes in vegetation coverage and structure due to long-term climate change or shorter-term extreme events such as droughts (Anderegg et al., 2013) also affect the partitioning of precipitation into evapotranspiration and runoff, sometimes involving complex feedbacks with the atmosphere such as in the Amazon region (Port et al., 2012; Saatchi et al., 2013). One model in the study by Davie et al. (2013) showed regionally diverse climate change effects on vegetation distribution and structure, which had a much weaker effect on global runoff than the structural and physiological CO_2 effects. As water, carbon, and vegetation dynamics evolve synchronously and interactively under climate change (Heyder et al., 2011; Gerten et al., 2013), it remains a challenge to disentangle the individual effects of climate, CO_2, and land cover change on the water cycle.

(a) Impact of climate change including physiological and structural crop responses to increased atmospheric CO_2



(b) Impact of climate change only

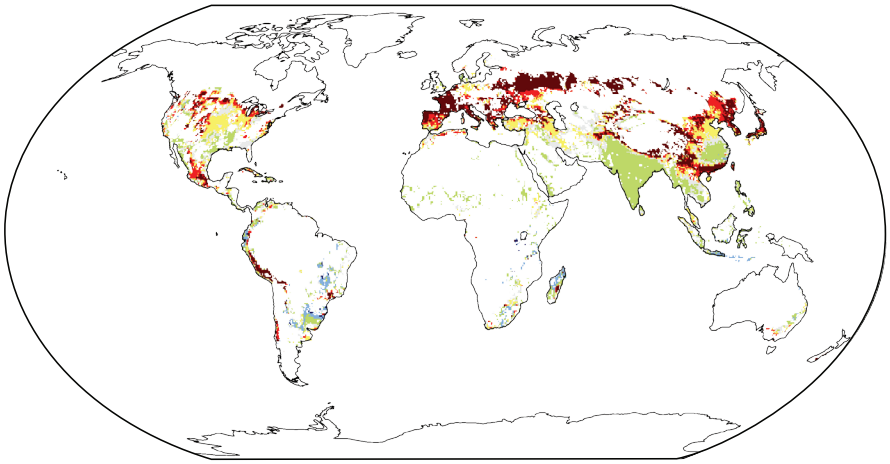




Figure VW-1 | Percentage change in net irrigation requirements of 11 major crops from 1971–2000 to 2070–2099 on areas currently equipped for irrigation, assuming current management practices. (a) Impact of climate change including physiological and structural crop responses to increased atmospheric CO_2 concentration (co-limitation by nutrients not considered). (b) Impact of climate change only. Shown is the median change derived from climate change projections by 19 General Circulation Models (GCMs; based on the Special Report on Emission Scenarios (SRES) A2 emissions scenario) used to force a vegetation and hydrology model. (Modified after Konzmann et al., 2013.)

References

Alkama, R., M. Kageyama, and G. Ramstein, 2010: Relative contributions of climate change, stomatal closure, and leaf area index changes to 20th and 21st century runoff change: a modelling approach using the Organizing Carbon and Hydrology in Dynamic Ecosystems (ORCHIDEE) land surface model. *Journal of Geophysical Research: Atmospheres*, **115(D17)**, D17112, doi:10.1029/2009JD013408.

Alkama, R., B. Decharme, H. Douville, and A. Ribes, 2011: Trends in global and basin-scale runoff over the late twentieth century: methodological issues and sources of uncertainty. *Journal of Climate*, **24(12)**, 3000-3014.

Anderegg, W.R.L., J.M. Kane, and L.D.L. Anderegg, 2013: Consequences of widespread tree mortality triggered by drought and temperature stress. *Nature Climate Change*, **3**, 30-36.

Andreu-Hayles, L., O. Planells, E. Gutierrez, E. Muntan, G. Helle, K.J. Anchukaitis, and G.H. Schleser, 2011: Long tree-ring chronologies reveal 20th century increases in water-use efficiency but no enhancement of tree growth at five Iberian pine forests. *Global Change Biology*, **17(6)**, 2095-2112.

Betts, R.A., O. Boucher, M. Collins, P.M. Cox, P.D. Falloon, N. Gedney, D.L. Hemming, C. Huntingford, C.D. Jones, D.M.H. Sexton, and M.J. Webb, 2007: Projected increase in continental runoff due to plant responses to increasing carbon dioxide. *Nature*, **448(7157)**, 1037-1041.

Boucher, O., A. Jones, and R.A. Betts, 2009: Climate response to the physiological impact of carbon dioxide on plants in the Met Office Unified Model HadCM3. *Climate Dynamics*, **32(2-3)**, 237-249.

Brolsma, R.J., M.T.H. van Vliet, and M.F.P. Bierkens, 2010: Climate change impact on a groundwater-influenced hillslope ecosystem. *Water Resources Research*, **46(11)**, W11503, doi:10.1029/2009WR008782.

Cao, L., G. Bala, K. Caldeira, R. Nemani, and G. Ban-Weiss, 2009: Climate response to physiological forcing of carbon dioxide simulated by the coupled Community Atmosphere Model (CAM3.1) and Community Land Model (CLM3.0). *Geophysical Research Letters*, **36(10)**, L10402, doi:10.1029/2009GL037724.

Crosbie, R.S., J.L. McCallum, G.R. Walker, and F.H.S. Chiew, 2010: Modelling climate-change impacts on groundwater recharge in the Murray-Darling Basin, Australia. *Hydrogeology Journal*, **18(7)**, 1639-1656.

Dai, A., T. Qian, K.E. Trenberth, and J.D. Milliman, 2009: Changes in continental freshwater discharge from 1948 to 2004. *Journal of Climate*, **22(10)**, 2773-2792.

Davie, J.C.S., P.D. Falloon, R. Kahana, R. Dankers, R. Betts, F.T. Portmann, D.B. Clark, A. Itoh, Y. Masaki, K. Nishina, B. Fekete, Z. Tessler, X. Liu, Q. Tang, S. Hagemann, T. Stacke, R. Pavlick, S. Schaphoff, S.N. Gosling, W. Franssen, and N. Arnell, 2013: Comparing projections of future changes in runoff and water resources from hydrological and ecosystem models in ISI-MIP. *Earth System Dynamics*, **4**, 359-374.

de Boer, H.J., E.I. Lammertsma, F. Wagner-Cremer, D.L. Dilcher, M.J. Wassen, and S.C. Dekker, 2011: Climate forcing due to optimization of maximal leaf conductance in subtropical vegetation under rising CO_2. *Proceedings of the National Academy of Sciences of the United States of America*, **108(10)**, 4041-4046.

Donohue, R.J., M.L. Roderick, T.R. McVicar, and G.D. Farquhar, 2013: Impact of CO_2 fertilization on maximum foliage cover across the globe's warm, arid environments. *Geophysical Research Letters*, **40(12)**, 3031-3035.

Fader, M., S. Rost, C. Müller, A. Bondeau, and D. Gerten, 2010: Virtual water content of temperate cereals and maize: present and potential future patterns. *Journal of Hydrology*, **384(3-4)**, 218-231.

Gagen, M., W. Finsinger, F. Wagner-Cremer, D. McCarroll, N.J. Loader, I. Robertson, R. Jalkanen, G. Young, and A. Kirchhefer, 2011: Evidence of changing intrinsic water-use efficiency under rising atmospheric CO_2 concentrations in Boreal Fennoscandia from subfossil leaves and tree ring $\partial^{13}C$ ratios. *Global Change Biology*, **17(2)**, 1064-1072.

Gedney, N., P.M. Cox, R.A. Betts, O. Boucher, C. Huntingford, and P.A. Stott, 2006: Detection of a direct carbon dioxide effect in continental river runoff records. *Nature*, **439(7078)**, 835-838.

Gerten, D., S. Rost, W. von Bloh, and W. Lucht, 2008: Causes of change in 20th century global river discharge. *Geophysical Research Letters*, **35(20)**, L20405, doi:10.1029/2008GL035258.

Gerten, D., J. Heinke, H. Hoff, H. Biemans, M. Fader, and K. Waha, 2011: Global water availability and requirements for future food production. *Journal of Hydrometeorology*, **12(5)**, 885-899.

Gerten, D., W. Lucht, S. Ostberg, J. Heinke, M. Kowarsch, H. Kreft, Z.W. Kundzewicz, J. Rastgooy, R. Warren, and H.J. Schellnhuber, 2013: Asynchronous exposure to global warming: freshwater resources and terrestrial ecosystems. *Environmental Research Letters*, **8**, 034032, doi:10.1088/1748-9326/8/3/034032.

Green, T.R., B.C. Bates, S.P. Charles, and P.M. Fleming, 2007: Physically based simulation of potential effects of carbon dioxide-altered climates on groundwater recharge. *Vadose Zone Journal*, **6(3)**, 597-609.

Haddeland, I., D.B. Clark, W. Franssen, F. Ludwig, F. Voss, N.W. Arnell, N. Bertrand, M. Best, S. Folwell, D. Gerten, S. Gomes, S.N. Gosling, S. Hagemann, N. Hanasaki, R. Harding, J. Heinke, P. Kabat, S. Koirala, T. Oki, J. Polcher, T. Stacke, P. Viterbo, G.P. Weedon, and P. Yeh, 2011: Multimodel estimate of the global terrestrial water balance: setup and first results. *Journal of Hydrometeorology*, **12(5)**, 869-884.

Heyder, U., S. Schaphoff, D. Gerten, and W. Lucht, 2011: Risk of severe climate change impact on the terrestrial biosphere. *Environmental Research Letters*, **6(3)**, 034036, doi:10.1088/1748-9326/6/3/034036.

Ito, A. and M. Inatomi, 2012: Water-use efficiency of the terrestrial biosphere: a model analysis focusing on interactions between the global carbon and water cycles. *Journal of Hydrometeorology*, **13(2)**, 681-694.

Joshi, M.M., J.M. Gregory, M.J. Webb, D.M.H. Sexton, and T.C. Johns, 2008: Mechanisms for the land/sea warming contrast exhibited by simulations of climate change. *Climate Dynamics*, **30(5)**, 455-465.

Keenan, T.F., D.Y. Hollinger, G. Bohrer, D. Dragoni, J.W. Munger, H.P. Schmid, and A.D. Richardson, 2013: Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise. *Nature*, **499(7458)**, 324-327.

Koehler, I.H., P.R. Poulton, K. Auerswald, and H. Schnyder, 2010: Intrinsic water-use efficiency of temperate seminatural grassland has increased since 1857: an analysis of carbon isotope discrimination of herbage from the Park Grass Experiment. *Global Change Biology*, **16(5)**, 1531-1541.

Konzmann, M., D. Gerten, and J. Heinke, 2013: Climate impacts on global irrigation requirements under 19 GCMs, simulated with a vegetation and hydrology model. *Hydrological Sciences Journal*, **58(1)**, 88-105.

Labat, D., Y. Godderis, J. Probst, and J. Guyot, 2004: Evidence for global runoff increase related to climate warming. *Advances in Water Resources*, **27(6)**, 631-642.

Leakey, A.D.B., E.A. Ainsworth, C.J. Bernacchi, A. Rogers, S.P. Long, and D.R. Ort, 2009: Elevated CO_2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *Journal of Experimental Botany*, **60(10)**, 2859-2876.

Lewis, S.L., J. Lloyd, S. Sitch, E.T.A. Mitchard, and W.F. Laurance, 2009: Changing ecology of tropical forests: evidence and drivers. *Annual Review of Ecology Evolution and Systematics*, **40**, 529-549.

Loader, N.J., R.P.D. Walsh, I. Robertson, K. Bidin, R.C. Ong, G. Reynolds, D. McCarroll, M. Gagen, and G.H.F. Young, 2011: Recent trends in the intrinsic water-use efficiency of ringless rainforest trees in Borneo. *Philosophical Transactions of the Royal Society B*, **366(1582)**, 3330-3339.

Lorenz, C. and H. Kunstmann, 2012: The hydrological cycle in three state-of-the-art reanalyses: intercomparison and performance analysis. *Journal of Hydrometeorology*, **13(5)**, 1397-1420.

McCallum, J.L., R.S. Crosbie, G.R. Walker, and W.R. Dawes, 2010: Impacts of climate change on groundwater in Australia: a sensitivity analysis of recharge. *Hydrogeology Journal*, **18(7)**, 1625-1638.

McMahon, S.M., G.G. Parker, and D.R. Miller, 2010: Evidence for a recent increase in forest growth. *Proceedings of the National Academy of Sciences of the United States of America*, **107(8)**, 3611-3615.

Murray, S.J., P.N. Foster, and I.C. Prentice, 2012: Future global water resources with respect to climate change and water withdrawals as estimated by a dynamic global vegetation model. *Journal of Hydrology*, **448-449**, 14-29.

Nock, C.A., P.J. Baker, W. Wanek, A. Leis, M. Grabner, S. Bunyavejchewin, and P. Hietz, 2011: Long-term increases in intrinsic water-use efficiency do not lead to increased stem growth in a tropical monsoon forest in western Thailand. *Global Change Biology*, **17(2)**, 1049-1063.

Nugent, K.A. and H.D. Matthews, 2012: Drivers of future northern latitude runoff change. *Atmosphere-Ocean*, **50(2)**, 197-206.

Oliveira, P.J.C., E.L. Davin, S. Levis, and S.I. Seneviratne, 2011: Vegetation-mediated impacts of trends in global radiation on land hydrology: a global sensitivity study. *Global Change Biology*, **17(11)**, 3453-3467.

Peñuelas, J., J.G. Canadell, and R. Ogaya, 2011: Increased water-use efficiency during the 20th century did not translate into enhanced tree growth. *Global Ecology and Biogeography*, **20(4)**, 597-608.

Piao, S., P. Friedlingstein, P. Ciais, N. de Noblet-Ducoudre, D. Labat, and S. Zaehle, 2007: Changes in climate and land use have a larger direct impact than rising CO_2 on global river runoff trends. *Proceedings of the National Academy of Sciences of the United States of America*, **104(39)**, 15242-15247.

Port, U., V. Brovkin, and M. Claussen, 2012: The influence of vegetation dynamics on anthropogenic climate change. *Earth System Dynamics*, **3**, 233-243.

Reddy, A.R., G.K. Rasineni, and A.S. Raghavendra, 2010: The impact of global elevated CO_2 concentration on photosynthesis and plant productivity. *Current Science*, **99(1)**, 46-57.

Rosenthal, D.M. and N.J. Tomeo, 2013: Climate, crops and lacking data underlie regional disparities in the CO_2 fertilization effect. *Environmental Research Letters*, **8(3)**, 031001, doi:10.1088/1748-9326/8/3/031001.

Saatchi, S., S. Asefi-Najafabady, Y. Malhi, L.E.O.C. Aragão, L.O. Anderson, R.B. Myneni, and R. Nemani, 2013: Persistent effects of a severe drought on Amazonian forest canopy. *Proceedings of the National Academy of Sciences of the United States of America*, **110(2)**, 565-570.

Sterling, S.M., A. Ducharne, and J. Polcher, 2013: The impact of global land-cover change on the terrestrial water cycle. *Nature Climate Change*, **3**, 385-390.

Wiltshire, A., J. Gornall, B. Booth, E. Dennis, P. Falloon, G. Kay, D. McNeall, C. McSweeney, and R. Betts, 2013 : The importance of population, climate change and CO_2 plant physiological forcing in determining future global water stress. *Global Environmental Change*, **23(5)**, 1083-1097.

This cross-chapter box should be cited as:

Gerten, D., R. Betts, and P. Döll, 2014: Cross-chapter box on the active role of vegetation in altering water flows under climate change. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 157-161.

WE

The Water–Energy–Food/ Feed/Fiber Nexus as Linked to Climate Change

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Water, energy, and food/feed/fiber are linked through numerous interactive pathways and subject to a changing climate, as depicted in Figure CC-WE-1. The depth and intensity of those linkages vary enormously among countries, regions, and production systems. Energy technologies (e.g., biofuels, hydropower, thermal power plants), transportation fuels and modes, and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops and forages) may require significant amounts of water (Sections 3.7.2, 7.3.2, 10.2,10.3.4, 22.3.3, 25.7.2; Allan, 2003; King and Weber, 2008; McMahon and Price, 2011; Macknick et al., 2012a). In irrigated agriculture, climate, irrigating procedure, crop choice, and yields determine water requirements per unit of produced crop. In areas where water (and wastewater) must be pumped and/or treated, energy must be provided (Metcalf & Eddy, Inc. et al., 2007; Khan and Hanjra, 2009; EPA, 2010; Gerten et al., 2011). While food production, refrigeration, transport, and processing require large amounts of energy (Pelletier et al., 2011), a major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water (*robust evidence, high agreement*; Section 7.3.2, Box 25-10; Diffenbaugh et al., 2012; Skaggs et al., 2012). Food and crop wastes, and wastewater, may be used as sources of energy, saving not only the consumption of conventional nonrenewable fuels used in their traditional processes, but also the consumption of the water and energy employed for processing or treatment and disposal (Schievano et al., 2009; Oh et al., 2010; Olson, 2012). Examples of this can be found in several countries across all income ranges. For example, sugar cane byproducts are increasingly used to produce electricity or for cogeneration (McKendry, 2002; Kim and Dale, 2004) for economic benefits, and increasingly as an option for greenhouse gas mitigation.

Most energy production methods require significant amounts of water, either directly (e.g., crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (*robust evidence, high agreement*; Sections 10.2.2, 10.3.4, 25.7.4; and van Vliet et al., 2012; Davies et al., 2013. Water for biofuels, for example, under the International Energy Agency (IEA) Alternative Policy Scenario, which has biofuels production increasing to 71 EJ in 2030, has been reported by Gerbens-Leenes et al. (2012) to drive global consumptive irrigation water use from 0.5% of global renewable water resources in 2005 to 5.5% in 2030, resulting in increased pressure on freshwater resources, with potential negative impacts on freshwater ecosystems. Water is also required for mining (Section 25.7.3), processing, and residue disposal of fossil and nuclear fuels or their byproducts. Water for energy currently ranges from a few percent in most developing countries to more than 50% of freshwater withdrawals in some developed countries, depending on the country (Kenny et al., 2009; WEC, 2010). Future water requirements will depend on electricity demand growth, the portfolio of generation technologies and water management options employed (*medium evidence, high agreement*; WEC, 2010; Sattler et al.,

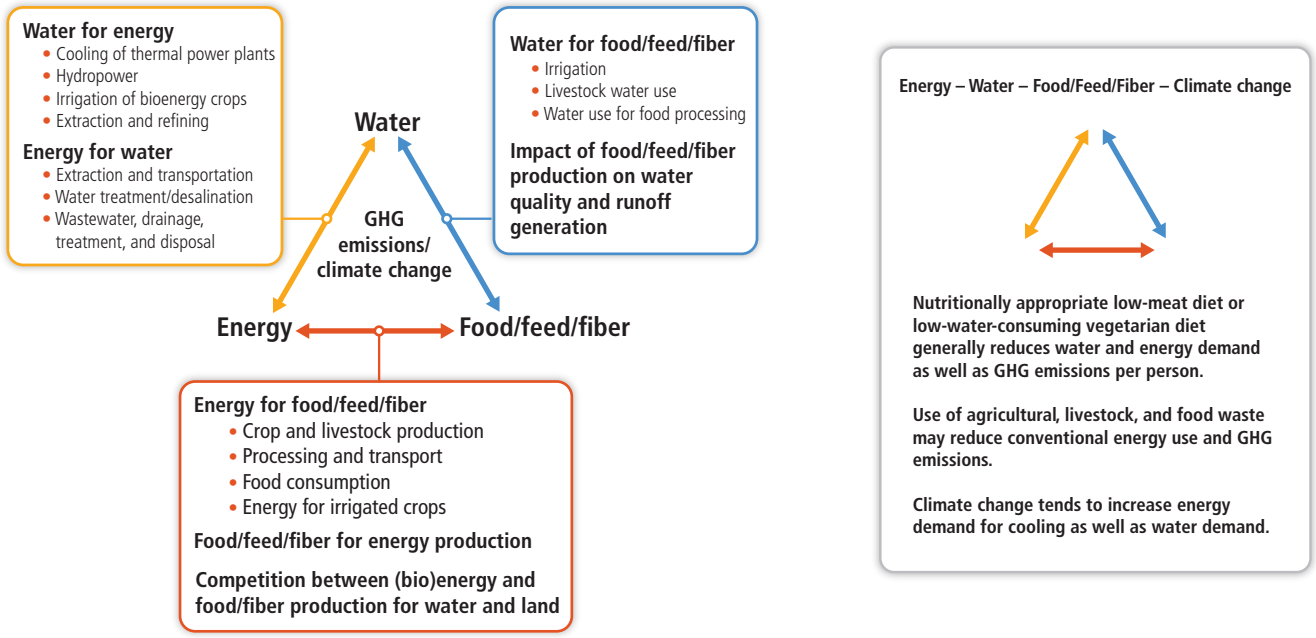

Figure WE-1 | The water–energy–food nexus as related to climate change. The interlinkages of supply/demand, quality and quantity of water, and energy and food/feed/fiber with changing climatic conditions have implications for both adaptation and mitigation strategies.

WE

2012). Future water availability for energy production will change due to climate change (*robust evidence, high agreement*; Sections 3.4, 3.5.1, 3.5.2.2.

Water may require significant amounts of energy for lifting, transport, and distribution and for its treatment either to use it or to depollute it. Wastewater and even excess rainfall in cities requires energy to be treated or disposed. Some non-conventional water sources (wastewater or seawater) are often highly energy intensive. Energy intensities per m^3 of water vary by about a factor of 10 between different sources, for example, locally produced potable water from ground/surface water sources versus desalinated seawater (Box 25-2, Tables 25-6, 25-7; Macknick et al., 2012b; Plappally and Lienhard, 2012). Groundwater (35% of total global water withdrawals, with irrigated food production being the largest user; Döll et al., 2012) is generally more energy intensive than surface water. In India, for example, 19% of total electricity use in 2012 was for agricultural purposes (Central Statistics Office, 2013), with a large share for groundwater pumping. Pumping from greater depth increases energy demand significantly—electricity use (kWh m^{-3} of water) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard, 2012). The reuse of appropriate wastewater for irrigation (reclaiming both water and energy-intense nutrients) may increase agricultural yields, save energy, and prevent soil erosion (*medium confidence*; Smit and Nasr, 1992; Jiménez-Cisneros, 1996; Qadir et al., 2007; Raschid-Sally and Jayakody, 2008). More energy efficient treatment methods enable poor quality ("black") wastewater to be treated to quality levels suitable for discharge into water courses, avoiding additional freshwater and associated energy demands (Keraita et al., 2008). If properly treated to retain nutrients, such treated water may increase soil productivity, contributing to increased crop yields/food security in regions unable to afford high power bills or expensive fertilizer (*high confidence*; Oron, 1996; Lazarova and Bahri, 2005; Redwood and Huibers, 2008; Jiménez-Cisneros, 2009).

Linkages among water, energy, food/feed/fiber, and climate are also strongly related to land use and management (*robust evidence, high agreement*; Section 4.4.4, Box 25-10). Land degradation often reduces efficiency of water and energy use (e.g., resulting in higher fertilizer demand and surface runoff), and compromises food security (Sections 3.7.2, 4.4.4). On the other hand, afforestation activities to sequester carbon have important co-benefits of reducing soil erosion and providing additional (even if only temporary) habitat (see Box 25-10) but may reduce renewable water resources. Water abstraction for energy, food, or biofuel production or carbon sequestration can also compete with minimal environmental flows needed to maintain riverine habitats and wetlands, implying a potential conflict between economic and other valuations and uses of water (*medium evidence, high agreement*; Sections 25.4.3, 25.6.2, Box 25-10). Only a few reports have begun to evaluate the multiple interactions among energy, food, land, and water and climate (McCornick et al., 2008; Bazilian et al., 2011; Bierbaum and Matson, 2013), addressing the issues from a security standpoint and describing early integrated modeling approaches. The interaction among each of these factors is influenced by the changing climate, which in turn impacts energy and water demand, bioproductivity, and other factors (see Figure CC-WE-1 and Wise et al., 2009), and has implications for security of supplies of energy, food, and water; adaptation and mitigation pathways; and air pollution reduction, as well as the implications for health and economic impacts as described throughout this Assessment Report.

The interconnectivity of food/fiber, water, land use, energy, and climate change, including the perhaps not yet well understood cross-sector impacts, are increasingly important in assessing the implications for adaptation/mitigation policy decisions. Fuel–food–land use–water–greenhouse gas (GHG) mitigation strategy interactions, particularly related to bioresources for food/feed, power, or fuel, suggest that combined assessment of water, land type, and use requirements, energy requirements, and potential uses and GHG impacts often epitomize the interlinkages. For example, mitigation scenarios described in the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (IPCC, 2011) indicate up to 300 EJ of biomass primary energy by 2050 under increasingly stringent mitigation scenarios. Such high levels of biomass production, in the absence of technology and process/management/operations change, would have significant implications for land use, water, and energy, as well as food production and pricing. Consideration of the interlinkages of energy, food/feed/fiber, water, land use, and climate change is increasingly recognized as critical to effective climate resilient pathway decision making (*medium evidence, high agreement*), although tools to support local- and regional-scale assessments and decision support remain very limited.

References

Allan, T., 2003: Virtual water – the water, food, and trade nexus: useful concept or misleading metaphor? *Water International*, **28(1)**, 4-10.

Bazilian, M., H. Rogner, M. Howells, S. Hermann, D. Arent, D. Gielen, P. Steduto, A. Mueller, P. Komor, R.S.J. Tol, and K. Yumkella, 2011: Considering the energy, water and food nexus: towards an integrated modelling approach. *Energy Policy*, **39(12),** 7896-7906.

Bierbaum, R. and P. Matson, 2013: Energy in the context of sustainability. *Daedalus*, **142(1)**, 146-161.

Davies, E., K. Page, and J.A. Edmonds, 2013: An integrated assessment of global and regional water demands for electricity generation to 2095. *Advances in Water Resources*, **52**, 296-313, doi:10.1016/j.advwatres.2012.11.020.

Diffenbaugh, N., T. Hertel, M. Scherer, and M. Verma, 2012: Response of corn markets to climate volatility under alternative energy futures. *Nature Climate Change*, **2**, 514-518.

Döll, P., H. Hoffmann-Dobrev, F.T. Portmann, S. Siebert, A. Eicker, M. Rodell, G. Strassberg, and B. Scanlon, 2012: Impact of water withdrawals from groundwater and surface water on continental water storage variations. *Journal of Geodynamics*, **59-60**, 143-156, doi:10.1016/j.jog.2011.05.001.

EPA, 2010: *Evaluation of Energy Conservation Measures for Wastewater Treatment Facilities*. EPA 832-R-10-005, U.S. Environmental Protection Agency (EPA), Office of Wastewater Management, Washington, DC, USA, 222 pp., water.epa.gov/scitech/wastetech/upload/Evaluation-of-Energy-Conservation-Measures-for-Wastewater-Treatment-Facilities.pdf.

Gerbens-Leenes, P.W., A.R. van Lienden, A.Y. Hoekstra, and Th.H. van der Meer, 2012: Biofuel scenarios in a water perspective: the global blue and green water footprint of road transport in 2030. *Global Environmental Change*, **22(3)**, 764-775.

Gerber, N., M. van Eckert, and T. Breuer, 2008: *The Impacts of Biofuel Production on Food Prices: A Review*. ZEF – Discussion Papers on Development Policy, No. 127, Center for Development Research [Zentrum für Entwicklungsforschung (ZEF)], Bonn, Germany, 19 pp.

Gerten, D., H. Heinke, H. Hoff, H. Biemans, M. Fader, and K. Waha, 2011: Global water availability and requirements for future food production. *Journal of Hydrometeorology*, **12**, 885-899.

IPCC, 2011: Summary for Policymakers. In: *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Special Report of Working Group III of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlmer, and C. von Stechow (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3-26.

Jiménez-Cisneros, B., 1996: Wastewater reuse to increase soil productivity. *Water Science and Technology*, **32(12)**, 173-180.

Jiménez-Cisneros, B., 2009: 4.06 – Safe sanitation in low economic development areas. In: *Treatise on Water Science, Volume 4: Water-Quality Engineering* [Wilderer, P.A. (ed.)]. Reference Module in Earth Systems and Environmental Sciences, Academic Press, Oxford, UK, pp.147-200.

Kenny, J.F., N.L. Barber, S.S. Hutson, K.S. Linsey, J.K. Lovelace, and M.A. Maupin, 2009: *Estimated Use of Water in the United States in 2005*. U.S. Department of the Interior, U.S. Geological Survey (USGS) Circular 1344, USGS, Reston, VA, USA, 53 pp.

Keraita, B., B. Jiménez, and P. Drechsel, 2008: Extent and implications of agricultural reuse of untreated, partly treated and diluted wastewater in developing countries. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources*, **3(58)**, 15-27.

Khan, S. and M.A. Hanjra, 2009: Footprints of water and energy inputs in food production – global perspectives. *Food Policy*, **34**, 130-140.

Kim, S. and B. Dale, 2004: Global potential bioethanol production from wasted crops and crop residues. *Biomass and Bioenergy*, **26(4)**, 361-375.

King, C. and M.E. Webber, 2008: Water intensity of transportation. *Environmental Science and Technology*, **42(21)**, 7866-7872.

Lazarova, V. and A. Bahri, 2005: *Water Reuse for Irrigation: Agriculture, Landscapes, and Turf Grass*. CRC Press, Boca Raton, FL, USA, 408 pp.

McKendry, P., 2002: Energy production from biomass (part 1): overview of biomass. *Bioresource Technology*, **83(1)**, 37-46.

Macknick, J., R. Newmark, G. Heath, K.C. Hallett, J. Meldrum, and S. Nettles-Anderson, 2012a: Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. *Environmental Research Letters*, **7(4)**, 045802, doi:10.1088/1748-9326/7/4/045802.

Macknick, J., S. Sattler, K. Averyt, S. Clemmer, and J. Rogers, 2012b: Water implications of generating electricity: water use across the United States based on different electricity pathways through 2050. *Environmental Research Letters*, **7(4)**, 045803, doi:10.1088/1748-9326/7/4/045803.

McCornick, P.G., S.B. Awulachew, and M. Abebe, 2008: Water-food-energy-environment synergies and tradeoffs: major issues and case studies. *Water Policy*, **10**, 23-36.

McMahon, J.E. and S.K. Price, 2011: Water and energy interactions. *Annual Review of Environment and Resources*, **36**, 163-191.

Metcalf & Eddy, Inc. an AECOM Company, T. Asano, F. Burton, H. Leverenz, R. Tsuchihashi, and G. Tchobanoglous, 2007: *Water Reuse: Issues, Technologies, and Applications*. McGraw-Hill Professional, New York, NY, USA, 1570 pp.

Oh, S.T., J.R. Kim, G.C. Premier, T.H. Lee, C. Kim, and W.T. Sloan, 2010: Sustainable wastewater treatment: how might microbial fuel cells contribute. *Biotechnology Advances*, **28(6)**, 871-881.

Olson, G., 2012: *Water and Energy Nexus: Threats and Opportunities*. IWA Publishing, London, UK, 294 pp.

Oron, G., 1996: Soil as a complementary treatment component for simultaneous wastewater disposal and reuse. *Water Science and Technology*, **34(11)**, 243-252.

Pelletier, N., E. Audsley, S. Brodt, T. Garnett, P. Henriksson, A. Kendall, K.J. Kramer, D. Murphy, T. Nemeck, and M. Troell, 2011: Energy intensity of agriculture and food systems. *Annual Review of Environment and Resources*, **36**, 223-246.

Plappally, A.K. and J.H. Lienhard V, 2012: Energy requirements for water production, treatment, end use, reclamation, and disposal. *Renewable and Sustainable Energy Reviews*, **16(7)**, 4818-4848.

Qadir, M., D. Wichelns, L. Raschid-Sally, P. Singh Minhas, P. Drechsel, A. Bahri, P. McCornick, R. Abaidoo, F. Attia, S. El-Guindy, J.H.J. Ensink, B. Jiménez, J.W. Kijne, S. Koo-Oshima, J.D. Oster, L. Oyebande, J.A. Sagardoy, and W. van der Hoek, 2007: Agricultural use of marginal-quality water – opportunities and challenges. In: *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture* [Molden, D. (ed.)]. Earthscan Publications, Ltd., London, UK, pp. 425-458.

Raschid-Sally, L. and P. Jayakody, 2008: *Drivers and Characteristics of Wastewater Agriculture in Developing Countries: Results from a Global Assessment*. IWMI Research Report 127, International Water Management Institute (IWMI), Colombo, Sri Lanka, 29 pp.

Redwood, M. and F. Huibers, 2008: Wastewater irrigation in urban agriculture. In: *Water Reuse: An International Survey of Current Practice, Issues and Needs* [Jiménez, B. and T. Asano (ed.)]. IWA Publishing, London, UK, pp. 228-240.

Sattler, S., J. Macknick, D. Yates, F. Flores-Lopez, A. Lopez, and J. Rogers, 2012: Linking electricity and water models to assess electricity choices at water-relevant scales. *Environmental Research Letters*, **7(4)**, 045804, doi:10.1088/1748-9326/7/4/045804.

Schievano A., G. D'Imporzano, and F. Adani, 2009: Substituting energy crops with organic wastes and agro-industrial residues for biogas production. *Journal of Environmental Management*, **90(8)**, 2537-2541.

Skaggs, R., K. Hibbard, P. Frumhoff, T. Lowry, R. Middleton, R. Pate, V. Tidwell, J. Arnold, K. Averyt, A. Janetos, C. Izaurralde, J. Rice, and S. Rose, 2012: *Climate and Energy-Water-Land System Interactions*. PNNL 21185, Technical Report to the US Department of Energy in support of the National Climate Assessment, Pacific Northwest National Laboratory (PNNL), Richland, WA, USA, 152 pp.

Smit, J. and J. Nasr, 1992: Urban agriculture for sustainable cities: using wastes and idle land and water bodies as resources. *Environment and Urbanization*, **4(2)**, 141-152.

van Vliet, M.T.H., J.R. Yearsley, F. Ludwig, S. Vögele, D.P. Lettenmaier, and P. Kabat, 2012: Vulnerability of US and European electricity supply to climate change. *Nature Climate Change*, **2**, 676-681.

Wise, M., K. Calvin, A. Thomson, L. Clarke, B. Bond-Lamberty, R. Sands, S.J. Smith, A. Janetos, and J. Edmonds, 2009: Implications of limiting CO_2 concentrations for land use and energy. *Science*, **324**, 1183-1186.

WEC, 2010: *Water for Energy*. World Energy Council (WEC), London, UK, 51 pp.

This cross-chapter box should be cited as:

Arent, D.J., P. Döll, K.M. Strzepek, B.E. Jiménez Cisneros, A. Reisinger, F.L. Tóth, and T. Oki, 2014: Cross-chapter box on the water–energy–food/feed/fiber nexus as linked to climate change. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 163-166.

Chapters 1-20

1 Point of Departure

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This chapter should be cited as:
Burkett, V.R., A.G. Suarez, M. Bindi, C. Conde, R. Mukerji, M.J. Prather, A.L. St. Clair, and G.W. Yohe, 2014: Point of departure. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 169-194.

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Frequently Asked Questions

1.1: On what information is the new assessment based, and how has that information changed since the last report, the IPCC Fourth Assessment Report in 2007? 174

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Executive Summary

The evolution of the IPCC assessments of impacts, adaptation, and vulnerability indicates an increasing emphasis on human beings, their role in managing resources and natural systems, and the societal impacts of climate change. The expanded focus on societal impacts and responses is evident in the composition of the IPCC author teams, the literature assessed, and the content of the IPCC assessment reports. Characteristics in the evolution of the Working Group II assessment reports are an increasing attention to (1) adaptation limits and transformation in social and natural systems; (2) synergies between multiple variables and factors that affect sustainable development; (3) risk management; and (4) institutional, social, cultural, and value-related issues. {1.1, 1.2}

The literature available for assessing climate change impacts, adaptation, and vulnerability more than doubled between 2005 and 2010, allowing for a more robust assessment that supports policymaking (*high confidence*). The diversity of the topics and regions covered by the literature has similarly expanded, as has the geographic distribution of authors contributing to the knowledge base for climate change assessments. Authorship of literature from developing countries has increased, although still representing a small fraction of the total. This unequal distribution of literature presents a challenge to the production of a comprehensive and balanced global assessment. {1.1.1, Figure 1-1}

Rapidly advancing climate science provides policy-relevant information that creates opportunities for decision making that can lead to climate-resilient development pathways (*robust evidence, medium agreement*). Climate change is just one of many stressors that influence resilience. The decisions that societies make within this opportunity space, also informed by observation, experience, and other factors, affect outcomes in human and natural systems. {1.1.1, 1.1.4, Figure 1-5}

Adaptation has emerged as a central area of climate change research, in country level planning, and in the implementation of climate change strategies (*high confidence*). The body of literature, including government and private sector reports, shows an increased focus on adaptation opportunities and the interrelations between adaptation, mitigation, and alternative sustainable pathways. The literature shows an emergence of studies on transformative processes that take advantage of synergies between adaptation planning, development strategies, social protection, and disaster risk reduction and management. {1.1.4}

As a core feature and innovation of IPCC assessment, major findings are presented with defined, calibrated language that communicates the strength of scientific understanding, including uncertainties and areas of disagreement. Each finding is supported by a traceable account of the evaluation of evidence and agreement. {1.1.2.2, Box 1-1}

Impacts assessed in this report are based on climate model projections using both the IPCC Special Report on Emission Scenarios (SRES) and the new Representative Concentration Pathway (RCP) scenarios. The RCPs span the range of SRES scenarios for long-lived greenhouse gases, but they have a narrower range in terms of emissions of ozone and aerosol precursors and related pollutants. The SRES scenarios were used in the Third Assessment Report (TAR) and the Fourth Assessment Report (AR4). With AR5, the RCP scenarios present both emissions and greenhouse gas concentration pathways, and corresponding Shared Socioeconomic Pathways (SSPs) have been developed. The four RCPs describe different levels of mitigation leading to 21st century radiative forcing levels of about 2.6, 4.5, 6.0, and 8.5 W m^{-2}), whereas the SRES scenarios are policy-independent. {1.1.3, 1.3.3, 19.6.3.1, Boxes 21-1, 21.5.4, 24.3.3; see also WGI AR5 Chapters 1, 8, 11, 12}

1

1.1. The Setting

This chapter describes the information basis for the Fifth Assessment Report (AR5) of IPCC Working Group II (WGII) and the rationale for its structure. As the starting point of WGII AR5, the chapter begins with an analysis of how the literature for the assessment has developed through time and proceeds with an overview of how the framing and content of the WGII reports have changed since the first IPCC report was published in 1990. The future climate scenarios used in AR5 are a marked change from those used in the Third (TAR, 2001) and Fourth (AR4, 2007) Assessment Reports; this shift is described here, along with the new AR5 guidance for communicating scientific uncertainty. The chapter provides a summary of the most relevant key findings from the IPCC *Special Report on Renewable Energy Sources and Climate Change Mitigation* (IPCC, 2011), the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (IPCC, 2012), and the AR5 Working Group I (*The Physical Science Basis*) and AR5 Working Group III (*Mitigation of Climate Change*). Collectively these recent reports, new scenarios, and other advancements in climate change science set the stage for an assessment of impacts, adaptation, and vulnerability that could potentially overcome many of the limitations identified in the IPCC WGII AR4, particularly with respect to the human dimensions of climate change.

The critical review and synthesis of the scientific literature published since October 2006 (effective cutoff date for AR4) has required an expanded multidisciplinary approach that, in general, has focused more heavily on societal impacts and responses. This includes an assessment of impacts associated with coupled socio-ecological systems and the rapid emergence of research on adaptation and vulnerability.

WGII AR5 differs from the prior assessments primarily in the expanded outline and diversity of content that stems directly from the growth of the scientific basis for the assessment. WGII AR5 is published in two volumes (Part A: Global and Sectoral Aspects; Part B: Regional Aspects), permitting the presentation of more detailed regional analyses and an expanded coverage of the human dimensions such as adaptation. WGI AR5 was completed approximately 6 months in advance of WGII AR5, allowing the WGII authors more time to evaluate and include where possible the WGI findings; WGIII AR5 was developed almost in parallel with the WGII report.

The point of departure in the title alludes to the availability of new information concerning the interactions between climate change and other biophysical and societal stressors. Societal stressors include poverty and inequality, low levels of human development, and psychological, institutional, and cultural factors. Even in the presence of these multiple stressors, policy relevant information from scientific research, direct experience, and observation provides an opportunity space to choose and design climate-resilient development pathways (see Sections 1.1.4, 13.1.1, 14.2, 14.3; Figure 1-5).

1.1.1. Development of the Science Basis for the Assessment

The volume of literature available for assessing Climate Change Impacts, Adaptation, and Vulnerability (CCIAV) has grown significantly over the past 2 decades (Figure 1-1). A bibliometric analysis of reports produced with two bibliographic search tools (Scopus[1] and ISI Web of Science[2]) indicates that fewer than 1000 articles in journals, books, and conference proceedings were published in English on the topic of "climate change" between 1970 and 1990. By the end of 2012 the total number of such articles was reported as 102,573 (Scopus) and 62,155 (Web of Science). The current doubling rate of "climate change" publications remains short, less than 5 years: Scopus database lists 32,943 articles published between 1970 and 2005, and 76,130 published between 1970 and 2010. The number of publications per year on the topic of climate change impacts between 2005 and 2010 and on the topic of climate change adaptation between 2008 and 2010 has roughly doubled (Figure 1-1c). Thus, the total number of publications more than doubled from 2005 to 2010.

Since 1990 the geographic distribution of authors contributing to the climate change literature has expanded from Europe and North America to include a large fraction from Asia and Australasia. Literature from scientists affiliated with institutions in Africa and Central and South America, however, comprised approximately 5% of the total during 2001–2010 (Figure 1-1a). The proportion of literature focusing on individual countries within IPCC regions has also broadened over the past 3 decades, particularly for Asia (Figure 1-1b).[3] This brief chronicle neither differentiates across the various "subcategories" of the climate literature nor claims to be comprehensive in terms of literature produced in languages other than English.

Recent growth in the total volume of literature about climate change, and in particular that devoted to impacts and adaptation, has influenced the depth and scope of assessment reports produced by WGII, and it has enabled substantial advances in the assessment of the full range of impacts, adaptation, and vulnerability (Figure 1-1c). The unequal distribution of literature (Figure 1-1a,b,d) presents a challenge to the development of a comprehensive and balanced assessment of the global impacts of climate change. The geographical and topical distribution of literature is influenced by factors such as the availability of funding for scientific research, level of capacity building, regional experience with climate-related disasters, and the availability of long-term observational records.

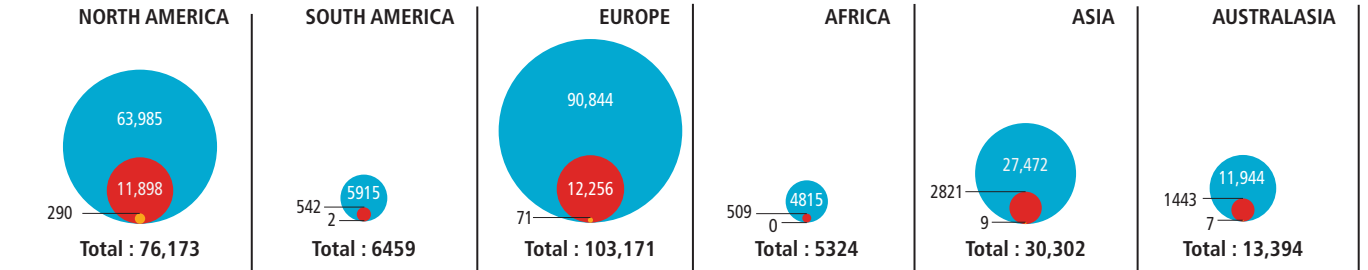
Literature published on the topic of "climate change" during 1970–1990 focused primarily on changes in the physical climate system and how these changes affected other aspects of the Earth's physical environment.

[1] Scopus is a bibliographic database owned by Elsevier that contains abstracts and citations for peer-reviewed literature in the scientific, medical, and social sciences (including arts and humanities). Scopus has more than 50 million bibliographic records (about 29 million from 1995 forward and about 21 million from 1823 to 1996), as of September 2013.

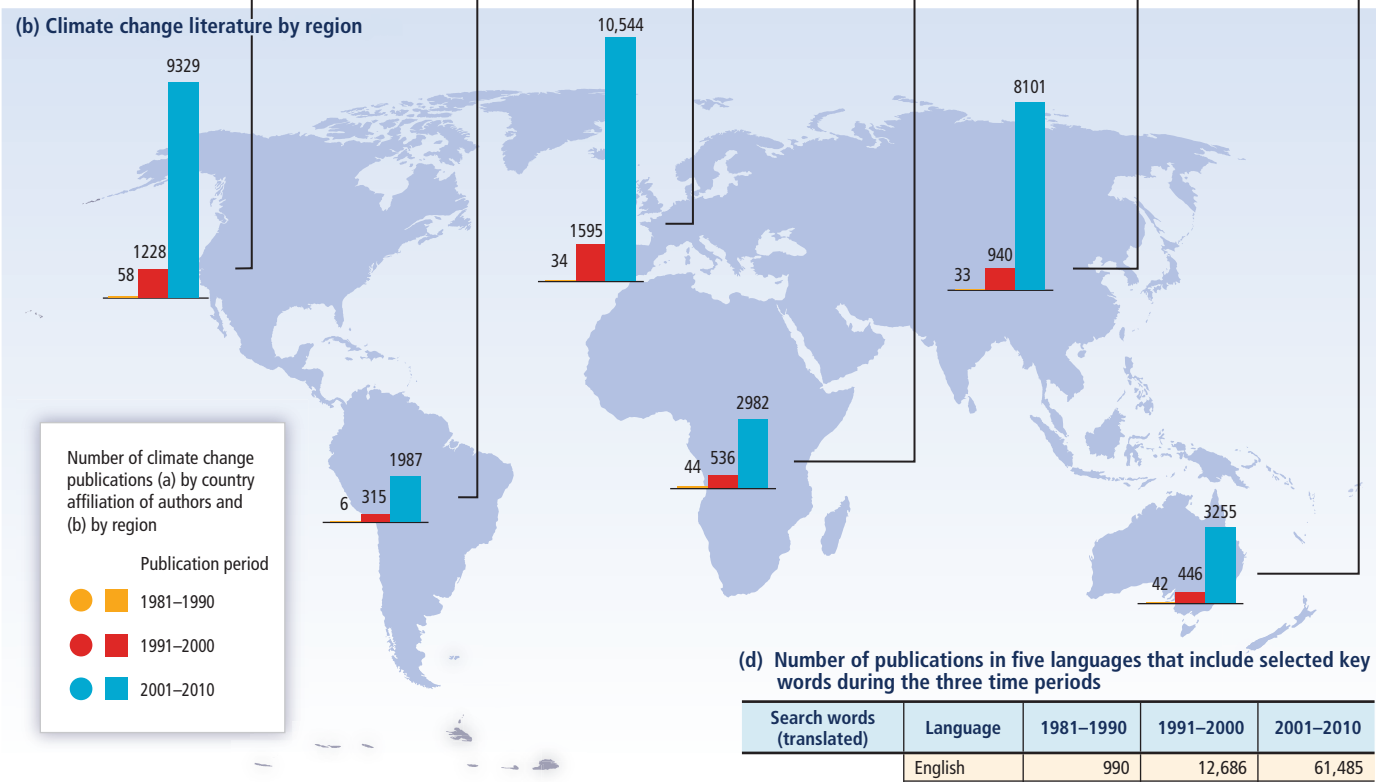
[2] Web of Science, owned by Thompson Reuters, is a bibliographic database of journals and conference proceedings for the sciences, social sciences, arts, and humanities. Web of Science includes records from over 12,000 journals and 148,000 conference proceedings dating from 1985 to present, as of September 2013.

[3] Russia, Greenland, and Iceland are included with Europe; Mexico is included with North America.

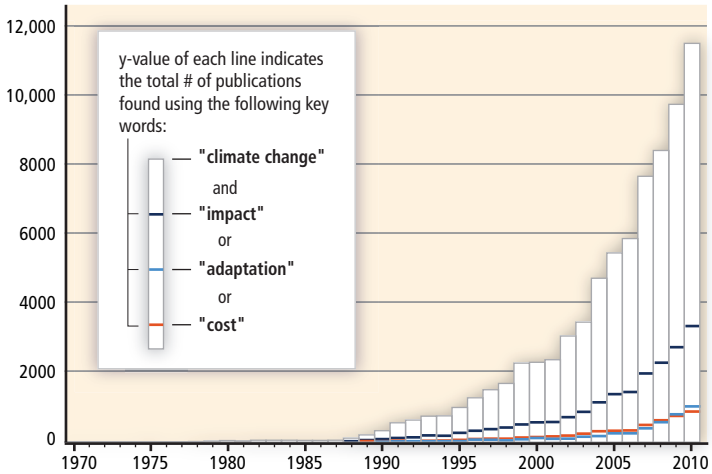
(a) Author affiliation



(b) Climate change literature by region



(c) Climate change literature in English, total and for selected topics (1970–2010)



(d) Number of publications in five languages that include selected key words during the three time periods

Search words (translated)	Language	1981–1990	1991–2000	2001–2010
"Climate change"	English	990	12,686	61,485
	Chinese	1454	6353	22,008
	French	1	108	815
	Russian	67	210	1443
	Spanish	3	82	1381
"Climate change" and "impacts"	English	232	3001	16,218
	Chinese	133	515	1780
	French	0	1	95
	Russian	0	72	403
	Spanish	0	7	103
"Climate change" and "adaptation"	English	14	373	3661
	Chinese	6	58	321
	French	0	7	110
	Russian	0	7	44
	Spanish	0	5	103
"Climate change" and "cost"	English	24	699	4099
	Chinese	1	22	162
	French	0	7	36
	Russian	0	1	24
	Spanish	0	2	11

Figure 1-1 | Number of climate-change publications listed in the Scopus bibliographic database and results of literature searches conducted in four other languages. (a) Number of publications in English (as of July, 2011) summed by country affiliation of all authors of climate change publications and binned into IPCC regions. Each publication can be counted multiple times (i.e., the number of different countries in the author affiliation list). (b) Number of climate change publications in English with individual countries mentioned in title, abstract, or key words (as of July, 2011) binned into IPCC regions for the decades 1981–1990, 1991–2000, and 2001–2010. Each publication can be counted multiple times if more than one country is listed. (c) Annual global number of publications in English on climate change and related topics: impacts, adaptation, and costs for the years 1970–2010, as of September 2013. (d) Number of publications in five languages that include the words "climate change" and "climate change" plus "adaptation," "impact," and "cost" (translated) in the title, abstract, or key words during the three decades ending in 2010. The following individuals conducted these literature searches during January, 2012–March, 2013: Valentin Przyluski (French), Huang Huanping (Chinese), Peter Zavialov and Vasily Kokorev (Russian), and Saúl Armendáriz Sánchez (Spanish).

Frequently Asked Questions

FAQ 1.1 | On what information is the new assessment based, and how has that information changed since the last report, the IPCC Fourth Assessment Report in 2007?

Thousands of scientists from around the world contribute voluntarily to the work of the IPCC, which was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988 to provide the world with a clear scientific assessment of the current scientific literature about climate change and its potential human and environmental impacts. Those scientists critically assess the latest scientific, technical, and socioeconomic information about climate change from many sources. Priority is given to peer-reviewed scientific, technical, and social-economic literature, but other sources such as reports from government and industry can be crucial for IPCC assessments.

The body of scientific information about climate change from a wide range of fields has grown substantially since 2007, so the new assessment reflects the large amount that has been learned in the past 6 years. To give a sense of how that body of knowledge has grown, between 2005 and 2010 the total number of publications just on climate change impacts, the focus of Working Group II, more than doubled. There has also been a tremendous growth in the proportion of that literature devoted to particular countries or regions.

The proportion of climate-change literature in engineering journals has not changed appreciably over the past 4 decades, but there was a significant increase in the proportion of literature published in biological and agricultural science journals. The proportion of the literature on the topic of "climate change" published in social science journals increased from 6% (1970s–1980s) to 9% (1990s–2000s). The themes covered by the literature on vulnerability to climate change have also expanded to issues of ethics, equity, and sustainable development. From the Scopus database, publications on the topic of climate change "impacts" crossed the threshold of 100 per year in 1991. Publications on climate change "adaptation" and societal "cost" reached this level in 2003.

Although authors continue to publish primarily in English, climate-change literature in other languages has also expanded. Literature searches in Chinese, French, Russian, and Spanish revealed a roughly fourfold or greater increase in literature published on the topic of "climate change" in each language during the past 2 decades (Figure 1-1d). Scientists from many countries tend to publish their work in English, as indicated by comparing the regional analysis and country affiliation of authors in Figure 1-1b with the results of the literature searches in the five languages. This process of "scientific internationalism," by which English becomes the primary language of scientific communication, has been described as a growing trend among Russian (Kirchik et al., 2012), Spanish (Alcaide et al., 2012), and French (Gingras and Mosbah-Natanson, 2010) researchers.

1.1.2. Evolution of the Working Group II Assessment Reports and Treatment of Uncertainty

1.1.2.1. Framing and Outlines of Working Group II Assessment Reports

The framing and contents of the IPCC WGII reports have evolved since the First Assessment Report (FAR; IPCC, 1990) as summarized in Figure 1-2. Four characteristics of this evolution are an increasing attention to (1) adaptation limits and transformation in societal and natural systems; (2) synergies between multiple variables and factors that affect sustainable development; (3) risk management; and (4) institutional, social, cultural, and value-related issues. WGII now focuses on understanding the interactions between the natural climate system, ecosystems, human beings, and societies, this being on top of the long-standing emphasis on the biogeophysical impacts of climate change on sectors and regions.

The WGII FAR (296 pages) was organized into six major sectors: agriculture and forestry; terrestrial ecosystems; water resources; human settlements; oceans and coastal zones; and snow, ice, and permafrost. The report focused on the anticipated climate changes for a doubling of carbon dioxide (CO_2). The FAR Summary for Policymakers (SPM) highlighted the coupling of anthropogenic non-climate stresses with climate variability and greenhouse gas (GHG) driven climate change. Given the state of the science in 1990, the FAR has understandably low confidence on some high-vulnerability topics (e.g., global agricultural potential may either increase or decrease), but is more quantitative on large-scale climate impacts (e.g., climatic zones shift poleward by hundreds of kilometers). Health impacts were vague, emphasizing ozone depletion and ultraviolet-B (UV-B) damage. The IPCC WGII 1992 Supplementary Report followed with four assigned topics (regional climate change; energy; agriculture and forestry; sea level rise) and was primarily a strategy report, for example, urging that studies of change in tropical cyclones are of highest priority (IPCC, 1992).

For the IPCC SAR (IPCC, 1996) WGII reviewed climate change impacts, vulnerability, and adaptation plus mitigation options for GHGs. There were two introductory primers, 18 chapters on impacts and adaptation (e.g., forests, rangelands, deserts, human settlements, agriculture, fisheries, financial services, human health), and seven chapters on sectoral mitigation (e.g., energy, industry, forests) but with cost analysis left to WGIII. The SAR made use of the new IPCC 1992 scenarios (IS92). Projections of 2100 sea level rise (15 to 95 cm) and temperature increase (1.0°C to 3.5°C) were similar to the FAR's doubled-CO_2 scenario.



Figure 1-2 | Tables of Contents for the Working Group II contributions to the IPCC Assessments since 1990. The First Assessment Report (FAR; IPCC, 1990) of IPCC Working Group II (WGII) focused on the impacts of climate change. For the Second Assessment Report (SAR; IPCC, 1996) the WGII contribution included mitigation and adaptation with the impacts assessment. With the Third Assessment Report (TAR; IPCC, 2001) and Fourth Assessment Report (AR4; IPCC, 2007) climate change mitigation reverted to WGIII, and WGII remained focused on impacts, adaptation, and vulnerability with an expanded effort on the regional scale.

The SAR notes "Impacts are difficult to quantify, and existing studies are limited in scope; detection [of climate-induced changes] will be difficult," but some specifics are given (e.g., the number of people at risk of flooding from storm surges from sea level rise; the increase in malaria incidence). Vegetation models are used to map out projected changes in major biomes (see WGII SAR SPM Figure 2) – the first prediction figure in a WGII SPM.

WGII TAR (IPCC, 2001b) retained impacts, adaptation, and vulnerability, leaving the topic of mitigation to WGIII. It included five sectoral chapters (water resources, ecosystems, coastal and marine, human settlements and energy, and financial services), eight regional chapters, plus chapters on (1) adaptation, sustainable development, and equity, and (2) vulnerability and reasons for concern. The TAR made the first strong conclusion on attributing impacts: "recent regional climate changes, particularly temperature increases, have already affected many physical and biological systems." Recent increases in floods and droughts, while affecting some human systems, could not be tied to GHG-driven climate change. The TAR introduced the "burning embers" diagram (SPM Figure 2, discussed in Chapters 18 and 19 of this report) as a way to represent "reasons for concern." The adaptive capacity, vulnerability, and key concerns for each region were laid out in detail (SPM, Table 2).

WGII AR4 (IPCC, 2007b,c) retained the basic structure of the TAR with chapters on sectors and regions. The first chapter of AR4, drawing from the expanded literature, provided an "Assessment of Observed Changes in Natural and Human Systems." AR4 incorporated several cross-chapter themes with case studies (such as impacts on deltas) as a unifying construct. Two graphics in the AR4 SPM (SPM Figure 1-2 and Table 1-1) give many examples of projected impacts of climate change, but the state of the science—both of WGI climate projections and WGII impacts—remained too uncertain at the time to give more quantitative estimates of the impacts or necessary adaptation.

This WGII fifth assessment continues and expands the sectoral and regional parts. The AR5 considers a wide and complex range of multiple stresses that influence the sustainability of human and ecological systems. The focus on climate change and related stressors, and the resulting vulnerability and risk, continues throughout this report, including the expanded "reasons for concern" (Chapters 2 and 19; see also Section 1.2.3).

1.1.2.2. Treatment of Uncertainties in IPCC Assessment Reports: A Brief History and Terms Used in the Fifth Assessment Report

An integral feature of IPCC reports is communication of the strength of and uncertainties in scientific understanding underlying assessment findings. Treatment of uncertainties and corresponding use of calibrated uncertainty language in IPCC reports have evolved across IPCC assessment cycles (Swart et al., 2009; Mastrandrea and Mach, 2011). In WGII, the use of calibrated language began in the SAR (1996), in which most chapters used qualitative levels of confidence in Executive Summary findings. With the TAR (2001), formal guidance across the Working Groups was developed (Moss and Schneider, 2000) recognizing that "guidelines such as these will never truly be completed," and an iterative process of learning and improvement of guidance has ensued, informed by experience in each assessment cycle (IPCC, 2005; Mastrandrea et al., 2010). Each subsequent guidance paper has presented related but distinct approaches for evaluating and communicating the degree of certainty in findings of the assessment process.

The AR5 Guidance Note (summarized in Box 1-1) continues to emphasize an overriding theme of clearly linking each key finding and corresponding assignment of calibrated uncertainty language to associated chapter text, as part of the traceable account of the author team's evaluation of evidence and agreement supporting that finding.

1.1.3. Scenarios Used as Inputs to Working Group II Assessments

A scenario is a storyline or image that describes a potential future, developed to inform decision making under uncertainty (Parson et al., 2007). Scenarios have been part of IPCC future climate projections since

Frequently Asked Questions

FAQ 1.2 | How is the state of scientific understanding and uncertainty communicated in this assessment?

While the body of scientific knowledge about climate change and its impacts has grown tremendously, future conditions cannot be predicted with absolute certainty. Future climate change impacts will depend on past and future socioeconomic development, which influences emissions of heat-trapping gases, the exposure and vulnerability of society and ecosystems, and societal capacity to respond.

Ultimately, anticipating, preparing for, and responding to climate change is a process of risk management informed by scientific understanding and the values of stakeholders and society. The Working Group II assessment provides information to decision makers about the full range of possible consequences and associated probabilities, as well as the implications of potential responses. To clearly communicate well-established knowledge, uncertainties, and areas of disagreement, the scientists developing this assessment report use specific terms, methods, and guidance to characterize their degree of certainty in assessment conclusions.

Box 1-1 | Communication of Uncertainty in the Working Group II Fifth Assessment

Based on the 'Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties' (Mastrandrea et al., 2010), the WGII AR5 relies on two metrics for communicating the degree of certainty in key findings:

- Confidence in the validity of a finding, based on the type, amount, quality, and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and the degree of agreement. Confidence is expressed qualitatively.
- Quantified measures of uncertainty in a finding expressed probabilistically (based on statistical analysis of observations, model results, or expert judgment).

Each finding has its foundation in an author team's evaluation of associated evidence and agreement. The type and amount of evidence available vary for different topics, and that evidence can vary in quality. The consistency of different lines of evidence can also vary. Beyond consistency of evidence, the degree of agreement indicates the consensus within the scientific community on a topic and the degree to which established, competing, or speculative scientific explanations exist.

The Guidance Note provides summary terms to describe the available evidence: *limited*, *medium*, or *robust*; and the degree of agreement: *low*, *medium*, or *high*. These terms are presented with some key findings. In many cases, author teams in addition evaluate their confidence about the validity of a finding, providing a synthesis of the evaluation of evidence and agreement. Levels of confidence include five qualifiers: *very low*, *low*, *medium*, *high*, and *very high*. Figure 1-3 illustrates the relationship between the summary terms for evidence and agreement and the confidence metric. There is flexibility in this relationship; increasing confidence is associated with increasing evidence and agreement, but different levels of confidence can be assigned for a given evidence and agreement statement. The degree of certainty in findings based on qualitative evidence is expressed using levels of confidence and summary terms.

In some cases, available evidence incorporates quantitative analyses, based on which uncertainties can be expressed probabilistically. In such cases, a finding can include calibrated likelihood language or a more precise presentation of probability. The likelihood terms and their corresponding probability ranges are presented below. Use of likelihood is not an alternative to use of confidence: an author team will have a level of confidence about the validity of a probabilistic finding. Unless otherwise indicated, findings assigned a likelihood term are associated with *high* or *very high* confidence. When authors evaluate the likelihood of some well-defined outcome having occurred or occurring in the future, the terms and associated meanings are:

Term*	Likelihood of the outcome
Virtually certain	99–100% probability
Very likely	90–100% probability
Likely	66–100% probability
About as likely as not	33–66% probability
Unlikely	0–33% probability
Very unlikely	0–10% probability
Exceptionally unlikely	0–1% probability

* Additional terms used more occasionally are *extremely likely*: 95–100% probability, *more likely than not*: >50–100% probability, and *extremely unlikely*: 0–5% probability.

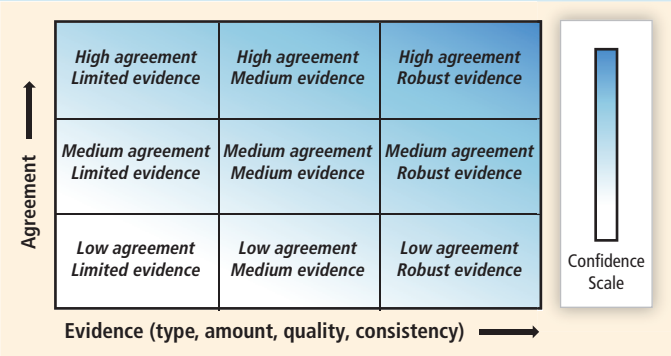


Figure 1-3 | Evidence and agreement statements and their relationship to confidence. The coloring increasing toward the top-right corner indicates increasing confidence. Generally, evidence is most robust when there are multiple, consistent independent lines of high-quality evidence.

the FAR (IPCC, 1990), where WGIII generated four scenarios (Bau = business-as-usual, B, C, and D) used by WGI to project climate change. The IPCC Supplementary Report (IPCC, 1992), a joint effort of WGI and WGIII, defined six new scenarios (IS92a–f) used in the SAR (1996). For the TAR (2001), the IPCC *Special Report on Emissions Scenarios* (SRES; Nakicenkovic et al., 2000) created many scenarios from four Integrated Assessment Models (IAMs), out of which a representative range of marker scenarios were selected (A1B, A1T, A1FI, A2, B1, B2). In the SRES, scenarios had had socioeconomic storylines but climate-mitigation options were not included. The SRES scenarios carried over into the AR4 (2007a,b) and formed the basis for the large number of ensemble climate simulations (Coupled Model Intercomparison Project Phase 3 (CMIP3)), which are still in use for climate-change studies relevant to WGII AR5.[4]

With AR5, the development of scenarios fundamentally changed from the IPCC-led SRES process. An ad hoc group of experts, anticipating AR5, built a new structure for scenarios called Representative Concentration Pathways (RCPs) (Moss et al., 2010; van Vuuren et al., 2011) using updated IAMs and intended to provide a flexible, interactive, and iterative approach to climate change scenarios. The four RCPs are keyed to a range of trajectories of GHG concentrations and climate forcing. They are labeled by their approximate radiative forcing (RF, W m^{-2}) that is reached during or near the end of the 21st century (RCP2.6, RCP4.5, RCP6.0, RCP8.5). The quantitative link between the socioeconomic pathway, human activities, and GHG emissions, and subsequently RF, is weaker or nonexistent with current RCP than with SRES scenarios. For example, the RCPs rely on a single parametric model (Meinshausen et al., 2011) to map from emissions to RF, whereas IPCC WGI traditionally assesses this critical linkage using the current state of scientific knowledge (see AR5 WGI Chapters 6, 11, 12, Annex II). In addition, socioeconomic scenarios, emissions, and subsequent radiative forcing pathways were not linked one-to-one in the initial RCPs; however, efforts to derive socioeconomic pathways consistent with each RCP are discussed in Chapter 20.

1.1.3.1. Comparison of RCP and SRES Scenarios

Whereas WGI AR5 is based primarily on results from the RCP CMIP5, the WGII AR5 also uses results from the SRES CMIP3, and thus identifies similar or parallel scenarios from each set. The radiative forcing from the SRES and RCP scenarios is compared in Figure 1-4a. For the latter half of the 21st century, SRES A1FI lies above all RCP and other SRES; SRES A2 has a similar trajectory to RCP8.5 with both reaching about 8 W m^{-2} by 2100; and SRES B1 approximately matches RCP4.5 with both leveling off at about 4 W m^{-2}. RCP6.0 starts similarly to both RCP4.5 and SRES B1, but after 2060 it increases to about 5 W m^{-2}. RCP2.6, a strong mitigation scenario with net CO_2 removal by 2100, falls well outside the SRES range B1 to A2, peaking at about 2.6 W m^{-2} in 2040 and dropping thereafter (WGI AR5 Figure 1-15, Tables AII.6.1 to AII.6.10).

Total RF does not adequately describe the differences in climate change between SRES and RCP scenarios. All RCPs adopted stringent air pollution mitigation policies and thus have much lower tropospheric ozone and aerosol abundances than the SRES scenarios, which ignored the role of air quality regulations (WGI AR5 Tables AII.2.16 to AII.2.22). In terms of ozone and particulate matter precursor emissions, there is almost no overlap between SRES and RCP scenarios (WGI AR5 Tables AII.2.16 to AII.2.22). In terms of surface ozone at the continental scale, after 2060 the RCPs are similar to low-end SRES B1 (WGI AR5 Tables AII.7.1 and AII.7.2).

Global mean surface temperature change for these scenarios is shown in Figure 1-4b, based on WGI AR5 (Chapters 11, 12; Tables AII.7.5 and AII.7.6) and WGI AR4 (Figure 10.26). For purposes here, that is, of understanding differences in impact studies using different scenarios, only model CMIP5 ensemble means are shown for the RCPs. If the standard deviation of the models were plotted, all RCPs would touch or overlap through the century (WGI AR5 Table AII.7.5), but even this range underestimates the uncertainties in temperature change for those scenarios (see WGI AR5 Chapter 12). The AR5 RCP data are taken directly from the CMIP5 runs, whereas the AR4 data are based on a simple model, parameterized to match the different CMIP3 models (see Figure 1-4 caption). In terms of temperature change, RCP8.5 is close to SRES A2, but below SRES A1FI. RCP4.5 follows SRES B2 up to 2060, but then drops to track SRES B1. RCP6.0 has lower temperature change to start, following SRES B1, but then increases toward SRES B2 by 2100. In general, scenarios SRES A1B, A1T, and B2 lie in the large gap between RCP8.5 and RCP4.5/6.0. The RCP2.6 temperature change stabilizes at about 1°C above the reference period (1986–2005). The other RCPS and all SRES scenarios span the range 1.8°C to 4.1°C for the 2090s. The CMIP5 reference period is about 0.6°C above earliest observing period 1850–1900 (WGI AR5 Chapter 2).

1.1.3.2. Shared Socioeconomic Pathways

Shared Socioeconomic Pathways (SSPs) are being generated (Arnell et al., 2011; Kriegler et al., 2012) to form more complete scenarios that link each RCP's climate path to a range of human development pathways. The SSPs include three elements: (1) storylines, which are descriptions of the state of the world; (2) IAM quantitative variables (such as population, gross domestic product (GDP), technology availability); and (3) other variables, not included in the IAMs, such as ecosystem productivity and sensitivity or governance index. With these elements a goal of the SSP effort is to characterize a global socioeconomic future for the 21st century as a reference for climate change analysis (O'Neill et al., 2012). Combined SSP–RCP scenarios are needed to support synthesis across all IPCC Working Groups and, particularly for WGII, to facilitate the use of new climate modeling results with impacts, adaptation, and vulnerability (IAV) research. Five basic SSPs have been proposed, representing a wide range of possible development pathways,

[4] The Coupled Model Intercomparison Project is an activity of the World Climate Research Programme's Working Group on Coupled Modelling. Climate model output from simulations of the past, present, and future climate archived mainly in 2005–2006 constituted Phase 3 of the Coupled Model Intercomparison Project (CMIP3). Similar climate simulations by an expanded set of models with a close off date of March 2013 are being used in AR5 and constitute Phase 5 of the project (CMIP5). CMIP3 used the SRES scenarios, and CMIP5 used the Reference Concentration Pathway (RCP) scenarios.

primarily at global or large regional scales. For each RCP it is expected that one or more SSP could lead to that climate path. Several chapters of this report refer to the SSPs in their discussion of analyses of future impacts and vulnerability. Chapter 20 (Section 20.6.1) describes SSPs in more detail, and Chapter 21 (Section 21.2.2) notes how the time lags in producing SSPs has limited the use of CMIP5–RCP scenarios in AR5.

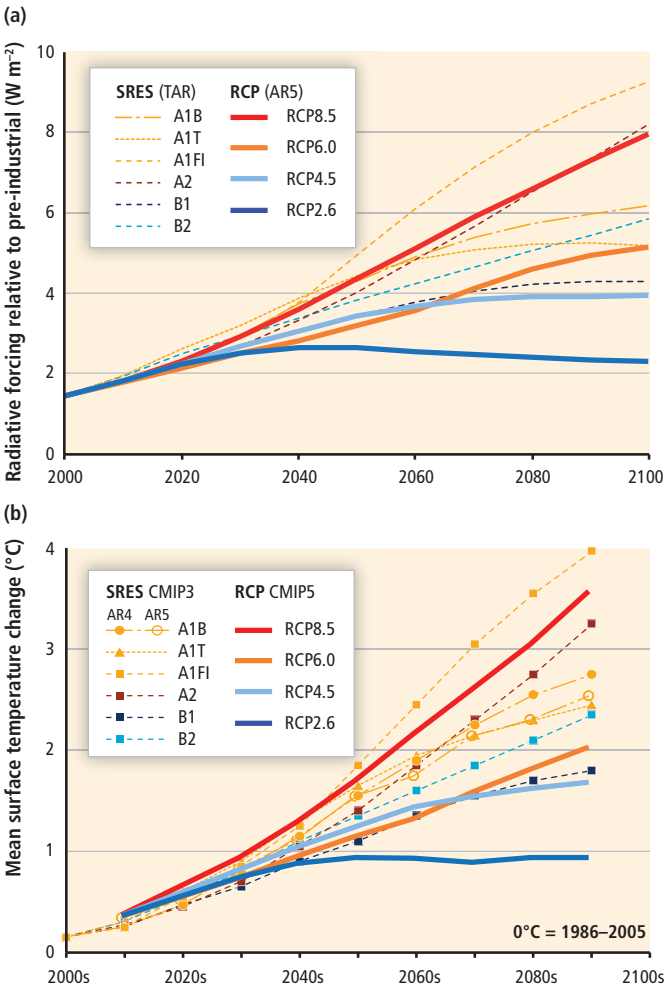


Figure 1-4 | (a) Projected radiative forcing (RF, W m^{-2}) and (b) global mean surface temperature change (°C) over the 21st century using the Special Report on Emissions Scenarios (SRES) and Representative Concentration Pathway (RCP) scenarios. RF for the RCPs are taken from their published CO_2-equivalent (Meinshausen et al., 2011), and RF for SRES are from the Third Assessment Report Appendix II (Table II.3.11). For RF derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5) models, see WGI (Section 12.3; Tables AII.6.9, 6.10). The ensemble total effective RF at 2100 for CMIP5 concentration-driven projections are 2.2, 3.8, 4.8, and 7.6 W m^{-2} for RCP2.6, RCP4.5, RCP6.0, and RCP8.5, respectively. The SRES RF are shifted upward by 0.12 W m^{-2} to match the RCPs at year 2000 because the climate change over the 21st century is driven primarily by the changes in RF and the offset is due primarily to improvements in model physics including the aerosol RF. For more details and comparison with pre-SRES scenarios, see WGI AR5 Chapter 1 (Figure 1-15). Temperature changes are decadal averages (e.g., 2020s = 2016–2025) based on the model ensemble mean CMIP5 data for the RCPs (colored lines). The same analysis is applied to CMIP3 SRES A1B (yellow circles). See WGI AR5 Chapters 11, 12; Table AII.7.5. The colored squares show the temperature change for all six SRES scenarios based on a simple climate model tuned to the CMIP3 models (WGI AR4 Figure 10.26). The difference between the yellow circles and yellow squares reflects differences between the simple model and analysis of the CMIP3 model ensemble in parallel with the CMIP5 data. For an assessment of uncertainties and *likely* ranges of temperature change, see WGI AR5 Figures 11.24, 11.25, 12.4, 12.5, 12.40.

1.1.4. Evolution of Understanding the Interaction between Climate Change Impacts, Adaptation, and Vulnerability with Human and Sustainable Development

The continuing increase in GHG emissions has highlighted the commitment to climate change and its varied impacts and has contributed to an increasing emphasis on vulnerability, adaptation, and sustainability. The possible range of socioeconomic trajectories in countries with low, medium, high, and very high human development is among the largest sources of uncertainty in scenario building and climate projections. A deeper understanding of development patterns, adaptation limits, and maladaptation, as well as options for more climate resilient pathways, has helped identify a larger range of potential climate change impacts and the risks they pose to society.

The first three WGII reports focused primarily on characterizing the biophysical impacts of climate change, with a progressively more elaborated understanding of economic and social impacts. The literature of the last decade indicates a more integrated understanding of the physical and social impacts of climate change. The extent and structure of WGII AR5 shows such advancements. The AR4 Synthesis Report asserted that "climate change impacts depend on the characteristics of natural and human systems, their development pathways and their specific locations" (IPCC, 2007d, p. 64). WGII AR4 Chapter 20 offered a catalog of multiple stresses jointly impacting people and communities and also highlighted questions of justice and equity in shaping development pathways in the context of climate change.

1.1.4.1. Vulnerability and Multiple Stressors

Climate-related risks interact with other biophysical and social stressors. Vulnerability is defined in the WGII TAR Glossary in terms of susceptibility and as a "function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity." Since then, the understanding of vulnerability has acquired increased complexity as a multidimensional concept, with more attention to the relation with structural conditions of poverty and inequality. WGII AR5 defines vulnerability simply as the propensity or predisposition to be adversely affected, and many chapters identify such vulnerabilities through societal risks, particularly in low-income economies. Recent studies suggest that climate impacts could slow down or reverse past development achievements; hinder global efforts on poverty reduction; and lead to human and environmental insecurity, displacement and conflict, maladaptation, and negative synergies (Jerneck and Olsson, 2008; Boyd and Juhola, 2009; Barnett and O'Neill, 2010; Ogallo, 2010; see also Sections 3.5.1, 8.2.4, 12.2.1, 12.4.1, 12.5.1, 13.2.1, 14.7).

The concept of resilience emerged from ecological sciences and has been increasingly used by social sciences. In climate change literature it describes the ability of a system to respond to disturbances, self-organize, learn, and adapt (Turner, 2010; Brown, 2013; WGII AR5 Glossary). Vulnerability, adaptation, and resilience are determined by multiple stressors, a combination of biophysical and social factors that jointly determine the propensity and predisposition to be adversely affected. For example, adaptive capacity in many urban centers in less

Frequently Asked Questions

FAQ 1.3 | How has our understanding of the interface between human, natural, and climate systems expanded since the 2007 IPCC Assessment?

Advances in scientific methods that integrate physical climate science with knowledge about impacts on human and natural systems have allowed the new assessment to offer a more comprehensive and finer-scaled view of the impacts of climate change, vulnerabilities to those impacts, and adaptation options, at a regional scale. That's important because many of the impacts of climate change on people, societies, infrastructure, industry, and ecosystems are the result of interactions between humans, nature, and specifically climate and weather, at the regional scale.

In addition, this new assessment from Working Group II greatly expands the use of the large body of evidence from the social sciences about human behavior and the human dimensions of climate change. It also reflects improved integration of what is known about physical climate science, which is the focus of Working Group I of the IPCC, and what is known about options for mitigating greenhouse gas emissions, the focus of Working Group III. Together this coordination and expanded knowledge inform a more advanced and finer-scaled, regionally detailed assessment of interactions between human and natural systems, allowing more detailed consideration of sectors of interest to Working Group II such as water resources, ecosystems, food, forests, coastal systems, industry, and human health.

developed countries is constrained by poverty, unemployment, quality of housing, or lack of access to potable water, sanitation, health care, and education interacting with land degradation, water stress, or biodiversity loss (Sections 8.2.4, 11.6.2, 22.4.4). Adaptation options and limits for high-end warming scenarios are often contextualized in relation to socioeconomic vulnerabilities and other stressors (Gupta et al., 2010; New et al., 2010; Stafford Smith et al., 2011; Brown, 2012; World Bank, 2012; see also Section 16.4.2.4).

1.1.4.2. Adaptation, Mitigation, and Development

Impacts of climate change will vary across regions and populations, through space and time, dependent on myriad factors including non-climate stressors and the extent of mitigation and adaptation. Changes in both climate and development are key drivers of the core components of risk (exposure, vulnerability, and physical hazards). The relations with development are complex and contested. There is disagreement about fundamental issues, such as the compatibility of development goals and climate change mitigation, the prioritization of responses (reducing consumption versus investment in sustainable technologies), and the stage of development at which countries should take action (see Box 1-2 for terms used to characterize stages of development) (Schipper, 2007; Grist, 2008; Brooks et al., 2009). The literature points to how inequalities, trade imbalances, intellectual property rights, gender injustice, or agricultural systems, *inter alia*, cannot be addressed with development focusing solely on increasing economic growth (Pogge, 2008; McMichael, 2009; Alston, 2011; UNDP, 2007, 2011; Büscher et al., 2012; OECD, 2013).

The recent literature shows increasing attention to questions of ethics, justice, and responsibilities relating to climate change (Timmons and Parks, 2007; O'Brien et al., 2010; Pelling, 2010; Arnold, 2011; Gardiner, 2011; Caney, 2012; Marino and Ribot, 2012). As basic resources such as energy, land, food, or water become threatened, inequalities and unfairness may deepen, leading to maladaptation and new forms of vulnerability. Responses to climate change may have consequences and outcomes that favor certain populations or regions. For example, there are increasing cases of land-grabbing and large acquisitions of land or water rights for industrial agriculture, mitigation projects, or biofuels that have negative consequences on local and marginalized communities (Borras et al., 2011; see also Section 14.7). Ethical perspectives are also important in relation to adaptation constraints and limits (see Section 16.7) and mitigation (see Section 1.3.4 and WGIII AR5).

Climate change impacts have become a central issue in the work of developmental organizations such as the United Nations specialized agencies, bilateral donor institutions, and non-governmental organizations (NGOs) that link adaptation concerns with ongoing development efforts. The increase in adaptation literature and experience, however, has led to the development of adaptation policies in many parts of the world, as reflected in four chapters here devoted to adaptation (14 to 17) and all of the regional chapters of this report. At the policy level, individual country National Adaptation Programmes of Action and National Communication reports to the United Nations Framework Convention on Climate Change (UNFCCC) had in the past focused primarily on physical climate change drivers and impacts. An analysis of National Communications documents submitted through 2004 by many of the Annex 1 countries, for example, showed that climate change impacts and adaptation receive very limited attention relative to the discussion of GHG emissions and mitigation policies (Gagnon-Lebrun and Agrawala, 2006). However, concern and actual progress toward adaptation is evident in Latin America (Gutierrez and Espinosa, 2010) and in recent National Communications of some non-Annex 1 countries, such as India (2012) and Iran (2010), which devoted a substantive part of their recent reports to the topic of adaptation.

Some researchers and institutions have sought to identify a continuum between development, adaptation strategies, and financing, including increasing attention to co-benefits with mitigation (USAID, 2008; Heltberg et al., 2009; Mearns and Norton, 2010; World Bank, 2010; Richardson et al., 2011; OECD, 2013). "Greener" development and market-based mechanisms are being explored as instruments to achieve synergies

Box 1-2 | Country Development Terminology

There are diverse approaches for categorizing countries on the basis of their level of development and for defining terms such as industrialized, developed, or developing. Table 1-1 presents selected categorizations used in this report. In the United Nations system, there is no established convention for the designation of developed and developing countries or areas (UN DESA, 2012). The United Nations Statistics Division specifies developed and developing regions based on "common practice." In addition, specific countries are designated as least developed countries, landlocked developing countries, small island developing states, and transition economies. Many countries appear in more than one of these categories. The World Bank uses income as the main criterion for classifying countries (World Bank, 2013). The UNDP aggregates indicators for life expectancy, educational attainment, and income into a single composite Human Development Index (HDI) (UNDP, 2013).

Table 1-1 | Selected country development categorizations used in this report.

Categorization approach	Categories	Criteria	Reference
United Nations	• Developing regions • Developed regions	Common practice	UN DESA (2012)
	Least developed countries	• Gross National Income (GNI) per capita • Human assets • Economic vulnerability to external shocks	UN DESA (2008)
	Landlocked developing countries	• Lack of territorial access to the sea • Remoteness and isolation from world markets • High transit costs	UN (2003)
	Small island developing states	Low-lying coastal countries sharing similar socioeconomic and environmental vulnerabilities	UN (1993)
	Economies in transition/transition economies	Countries changing from central planning to free markets	UN DESA (2013)
World Bank	• Low income • Lower middle income • Upper middle income • High income	GNI per capita	World Bank (2013)
UNDP	• Low human development • Medium human development • High human development • Very high human development	• GNI per capita • Life expectancy at birth • Mean years of schooling • Expected years of schooling	UNDP (2013)

between mitigation and adaptation efforts, development financing, and planning, and links to energy needs are some of the instruments explored. Large concerns remain, however, about the preconditions needed for market mechanisms to work as intended, the problems of carbon leakage, and the potential negative effects of some mitigation strategies (Liverman, 2010; see also Section 13.1.3 and WGIII AR5 Chapter 15).

1.1.4.3. Transformation and Climate-Resilient Pathways

Transformation—a change in the fundamental attributes of a system including altered goals or values—has emerged as a key concept in describing the dimensions, types, and rates of societal response to climate change. In the context of adaptation, we can distinguish between incremental and transformative adaptation, the latter referring to changes in the fundamental attributes of a system in response to climate change and its effects (WGII AR5 Glossary; Park et al., 2012). The *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) recognized transformation in technological, financial, regulatory, legislative, and administrative systems (IPCC, 2012; see Sections 1.3.1, 20.5). Recent literature points to changes in values, norms, belief systems, culture, and conceptions of progress and well-being as either facilitating or preventing transformation (Pelling, 2010; Stafford Smith et al., 2011; Kates et al., 2012; O'Brien, 2013). Transformation of this nature requires a particular understanding of risks, adaptive management, learning, innovation, and leadership, and may lead to climate resilient development pathways (see Section 1.2.3 and Chapter 20). Transformational change is not called for in all circumstances (Pelling, 2010) and in some cases may lead to negative consequences for some locations or social groups, contributing to social inequities (O'Brien, 2013). Climate resilient pathways include actions, strategies, and choices that reduce climate change impacts while assuring that risk management and adaptation can be implemented and sustained.

1.1.4.4. The Opportunity Space for Decision Making

Recognizing the need for policy-relevant science, much scientific activity tends to be coordinated through international programs that focus on, for example, biodiversity, desertification, food security, impacts on social practices and institutions, and monitoring sea level rise. The trend in

research is to create synergies across the sciences by including social and human sciences perspectives and transdisciplinarity. The production of information with non-scientific sources such as indigenous knowledge or stakeholder views is also enriching climate change research. This trend has led to the merging of relevant global programs of the international councils for science and for social science (ICSU and ISSC) under the umbrella "Future Earth" (see also ISSC and UNESCO, 2013). This expanded scientific focus combined with increased practice and experience with adaptation creates a new opportunity space for evaluating policy options and their risks in the search for climate resilient development pathways (Figure 1-5) (Sections 2.1, 2.4.3, 20.2, 20.3.3). Human and social-ecological systems can build resilience through adaptation, mitigation, and sustainable development.

Over the next few decades, global temperatures are projected to increase along broadly similar pathways, whether or not mitigation of GHGs occurs (Section 1.3.3). During this near-term era of committed climate change, risks will evolve as socioeconomic trends interact with the changing climate and societal responses, including adaptation, will influence near-term outcomes. In the second half of the 21st century and beyond, global temperature increases diverge across emissions scenarios. During this longer term era of climate options, near-term and ongoing mitigation efforts as well as development trajectories will determine the risks associated with climate change.

1.2. Major Conclusions of the Working Group II Fourth Assessment Report

This section presents highlights of the IPCC Fourth Assessment Report that are particularly relevant to AR5 as a point of departure. These highlights are drawn from the AR4 Synthesis Report, the WGII AR4

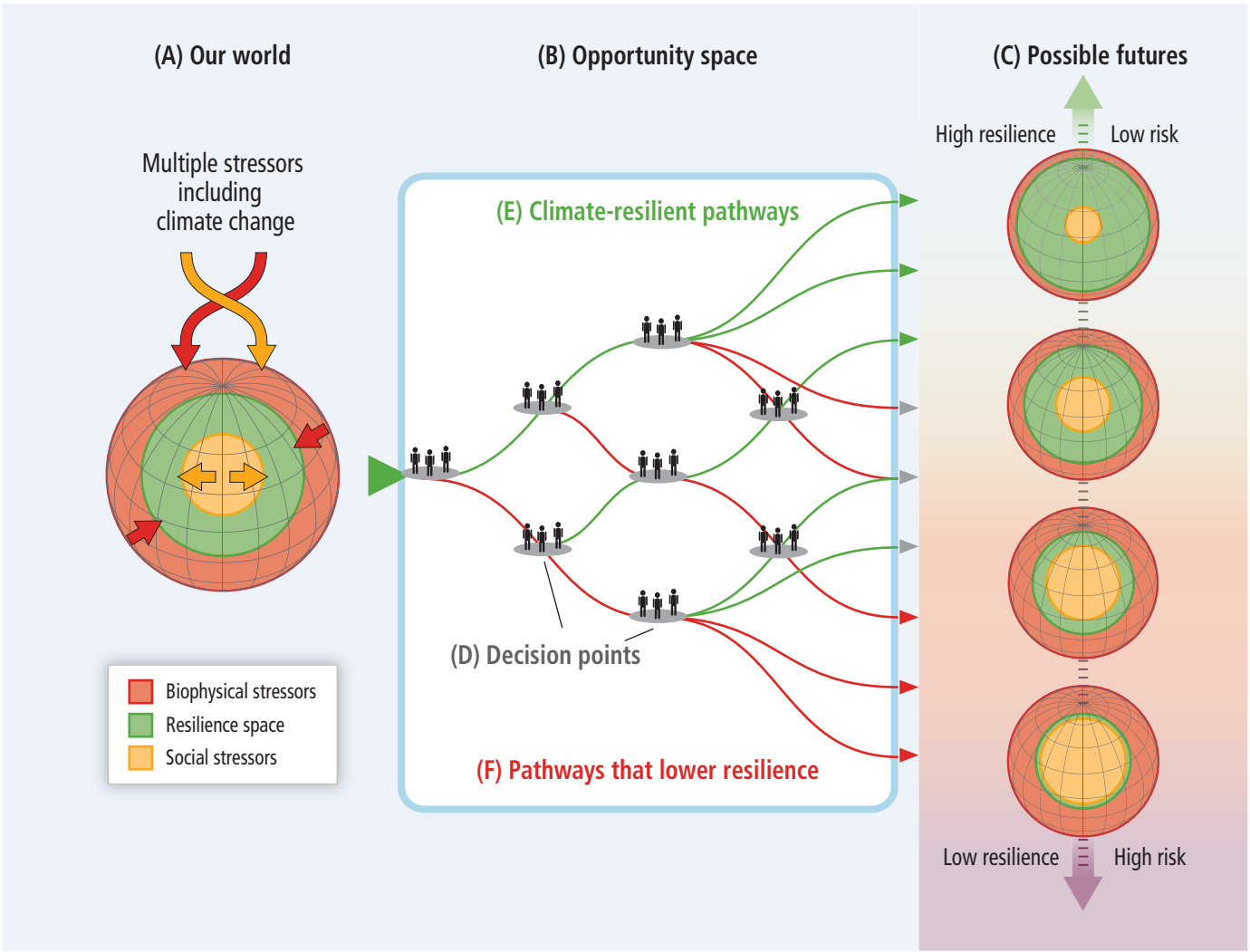


Figure 1-5 | Opportunity space and climate-resilient pathways. (a) Our world is threatened by multiple stressors that impinge on resilience from many directions, represented here simply as biophysical and social stressors. Stressors include climate change, climate variability, land-use change, degradation of ecosystems, poverty and inequality, and cultural factors. (b) Opportunity space refers to decision points and pathways that lead to a range of (c) possible futures with differing levels of resilience and risk. (d) Decision points result in actions or failures-to-act throughout the opportunity space, and together they constitute the process of managing or failing to manage risks related to climate change. (e) Climate-resilient pathways (in green) within the opportunity space lead to a more resilient world through adaptive learning, increasing scientific knowledge, effective adaptation and mitigation measures, and other choices that reduce risks. (f) Pathways that lower resilience (in red) can involve insufficient mitigation, maladaptation, failure to learn and use knowledge, and other actions that lower resilience; and they can be irreversible in terms of possible futures.

Summary for Policymakers (SPM), and the WGII AR4 chapter Executive Summaries.

1.2.1. Observed Impacts

Evidence presented in WGII AR4 Chapter 1 indicated that physical and biological systems on all continents and in most oceans were being affected by recent climate changes, particularly regional temperature increases (Rosenzweig et al., 2007, p. 81). In terrestrial ecosystems, warming trends were consistent with observed change in the timing of spring events and poleward and upward shifts in plant and animal ranges. The authors found that the geographical locations of observed changes during the period 1970–2004 are consistent with spatial patterns of atmospheric warming. The types of hydrologic changes reported included effects on snow, ice, and frozen ground; the number and size of glacial lakes; increased runoff and earlier spring peak discharge in many glacier- and snow-fed rivers; thermal structure and water quality of rivers and lakes; and more intense drought and heavy rains in some regions. The authors concluded from a synthesis of studies "that the spatial agreement between regions of significant warming and the locations of significant observed changes is *very unlikely* to be due solely to natural variability of temperatures or natural variability of the systems" (IPCC, 2007c, p. 9).

Observed regional impacts to human systems were less obviously attributed to anthropogenic climate change. AR4 authors concluded that **"There is *medium confidence* that other effects of regional climate change on natural and human environments are emerging, although many are difficult to discern due to adaptation and non-climatic drivers"** (IPCC, 2007d, p. 3). They presented evidence on the effects of temperature increases on agricultural and forest management at Northern Hemisphere (NH) higher latitudes (e.g., earlier spring planting of crops, alterations in disturbance regimes of forests due to fires and pests); on some aspects of human health (e.g., heat-related mortality in Europe, changes in infectious disease vectors in some areas, and allergenic pollen in NH high and mid-latitudes); and some human activities in the Arctic (e.g., hunting and travel over snow and ice) and in lower-elevation alpine areas (such as mountain sports).

The authors of AR4 concluded that "Recent climate changes and climate variations are beginning to have effects on many other natural and human systems. However, based on published literature, the impacts have not yet become established trends" (IPCC, 2007c, p. 9). Three examples were cited: in mountain regions melting glaciers enhanced risk of glacier lake outburst floods on settlements; in the Sahelian region of Africa warmer and drier conditions had detrimental effects on some crops; and in coastal areas sea level rise and human development contributed to losses of coastal wetlands and mangroves and to increases in damage from coastal flooding.

1.2.2. Key Vulnerabilities, Risks, and Reasons for Concern

In an effort to provide some insights into the seriousness of the impacts of climate change WGII TAR (Chapter 19) identified five "Reasons for Concern" (RFC) focusing on (1) unique and threatened systems, (2) extreme climate events, (3) distribution of impacts, (4) aggregate impacts, and (5) large-scale discontinuities (see Figure SPM-2 in IPCC, 2001b). Considering new evidence of observed changes on every continent, coupled with more thorough understanding of the concept of vulnerability, the AR4 concluded that the five "reasons for concern identified in the TAR remained a viable framework to consider key vulnerabilities" (IPCC, 2007d, p. 19).

The AR4 Synthesis Report SPM concluded with the following key message: **Responding to climate change involves an iterative risk management process that includes both adaptation and mitigation and takes into account climate change damages, co-benefits, sustainability, equity and attitudes to risk** (IPCC, 2007d, p. 22). The concept of risk (the confluence of likelihood and consequence) is the focus of this AR5 Report. All chapters, especially 2, 18, and 19, now focus on climate change, related stressors, resulting vulnerabilities, and associated risks. Correlating the risk-based framing of the RFC in WGII AR5 with the conclusions reported in the AR4 SPM is straightforward (italics indicate new terms that have been added to the RFC definitions from the IPCC, 2007d, p. 19):

- Risks to Unique and Threatened Systems: "There is new and stronger evidence of observed impacts of climate change on unique and vulnerable systems (such as polar and high mountain communities and ecosystems), with increasing levels of adverse impacts as temperatures increase."
- *Risks Associated with* Extreme Weather Events: "Responses to some recent extreme events reveal higher levels of vulnerability than the TAR. There is now higher confidence in the projected increases in droughts, heat waves, and floods, as well as their adverse impacts."
- *Risks Associated with the* Distribution of Impacts: "There are sharp differences across regions and those in the weakest economic position are often the most vulnerable to climate change. There is increasing evidence of greater vulnerability of specific groups such as the poor and elderly not only in developing but also in developed countries. Moreover, there is increased evidence that low-latitude and less developed areas generally face greater risk, for example, in dry areas and megadeltas."
- *Risks Associated with* Aggregate Impacts: "Compared to the TAR, initial net market-based benefits from climate change are projected to peak at a lower magnitude of warming, while damages would be higher for larger magnitudes of warming."
- Risks Associated with Large-Scale Discontinuities: "There is high confidence that global warming over many centuries would lead to a sea level rise contribution from thermal expansion alone that is projected to be much larger than observed over the 20th century, with loss of coastal area and associated impacts. There is better understanding than in the TAR that the risk of additional contributions to sea level rise from both the Greenland and possibly Antarctic ice sheets may be larger than projected by ice sheet models and could occur on century time scales."

WGII AR5 Chapters 18 and 19 recognize new evidence about the RFC in the context of risk. Chapter 18 expands our understanding of how observed and attributed impacts, vulnerabilities, and associated risks support the identification of the dependence of the RFC on temperature "up to the present." Chapter 19 extends this analysis to future temperatures. Both chapters demonstrate how accounting for both

components of risk in assessing the RFC permits a clearer understanding of "key vulnerabilities."

1.2.3. Interaction of Adaptation and Mitigation in a Policy Portfolio

A conclusion of AR4 is that coping with risks of climate change will involve a portfolio of initiatives that will evolve iteratively over time as new information about the workings of the climate system and new insights into how various responses are actually working and penetrating the global socioeconomic structure. The WGII AR4 concluded that (1) neither adaptation nor mitigation alone can avoid all climate change impacts, though together they can significantly reduce the risks of climate change; (2) adaptation is necessary in the short and longer term to address impacts, even for the lowest stabilization scenarios assessed, but there are barriers, limits, and costs, though these are not fully understood; (3) unmitigated climate change would *likely* exceed the adaptive capacity of natural, managed, and human systems in the long term; and (4) while many impacts can be reduced, delayed, or avoided by mitigation, delayed emission reductions "significantly constrain the opportunities to achieve lower stabilization levels and increase the risk of more severe climate change impacts." (IPCC, 2007d, p. 19).

WGII AR5 devotes considerable attention to the interface of adaptation and mitigation and the mechanisms for iterating decisions as described in a collection of chapters (16, 17, 19, and 20) designed explicitly for this purpose. These chapters build substantially upon key messages from the AR4 chapter entitled "Inter-relationships between adaptation and mitigation" (IPCC, 2007b, p. 747), including:

- Even the most stringent mitigation efforts cannot avoid further impacts of climate change in the next few decades, which makes adaptation unavoidable.
- Without mitigation, a magnitude of climate change is likely to be reached that makes adaptation impossible for some natural systems, while for most human systems it would involve very high social and economic costs.
- **"Creating synergies between adaptation and mitigation can increase the cost-effectiveness of actions and make them more attractive to stakeholders, including potential funding agencies (medium confidence)."** Such synergies, however, provide no guarantee that resources are used in the most efficient manner and opportunities for synergies are greater in some sectors (e.g., agriculture and forestry) than others (e.g., energy, health, and coastal systems).
- **"It is not yet possible to answer the question as to whether or not investment in adaptation would buy time for mitigation (high confidence)."** Barriers to understanding the trade-offs of the immediate benefits of localized adaptation and the longer term global benefits of mitigation, coupled with the limitation of models to simulate the intricacies of the interactions of the two, present a challenge to designing and implementing an "optimal mix" of response strategies.
- **"People's capacities to adapt and mitigate are driven by similar sets of factors (high confidence).** These factors represent a generalized response capacity that can be mobilized for both adaptation and mitigation." The authors noted that even societies with high adaptive capacity can be vulnerable to climate change, variability, and extremes.

1.3. Major Conclusions of More Recent IPCC Reports

Since publication of the AR4 in 2007, the IPCC has produced two Special Reports: the *Special Report on Renewable Energy Sources and Climate Change Mitigation*, produced by Working Group III and published in 2011; and the *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, produced jointly by WGI and WGII and published in 2012. In addition, the AR5 cycle has staggered the assessment work for its three working groups. WGI AR5 was released in September 2013, and WGIII AR5 will be published after WGII AR5 in 2014. In this section we summarize the major conclusions of the SREX, the SRREN, WGI AR5, and preliminary findings from WGIII AR5. We focus on the key findings, framings, and conceptual innovations these reports bring to WGII AR5.

One common theme that cuts across the Working Groups is the connection of three basic elements of climate change: (1) detection of climate change or its impacts; (ii) attribution of that observed climate change to the increases in GHGs (i.e., human cause, WGI) or attribution of local impacts to the observed climate change in that region; and (3) projection of these impacts and climate change into the 21st century. Table 1-2 gives a summary of phenomena for which such detection,

Trend

- Increasing overall
- Decreasing overall
- More regions increasing than decreasing
- More regions decreasing than increasing
- Regionally varies or no clear trend

Attribution

- Attributable to observed climate change
- Attributable to human influence

Projected

- Occurs in 21st century

Confidence assessment

HC	***High*** or ***Very High*** confidence
MC	***Medium*** confidence
LC	***Low*** confidence
X	***Very low*** confidence or No formal confidence level given
–	No explicit assessment made

Findings assigned a likelihood term are associated with high or very high confidence.

Likelihood assessment

****	*Virtually certain 99–100%*
***	*Extremely likely 95–100%*
**	*Very likely 90–100%*
*	*Likely 66–100%*

Table 1-2 | Confidence in the observation, attribution, and projection of changes in climate system phenomena.

	Phenomenon	Change	Observed to 2010 (X-axis, Figure 1-6)	Y-axis, Figure 1-6		Source
				Attribution	Projected 2050-2100	
1	Greenhouse gases: CO_2, CH_4, N_2O	↑	****	**** ■	**** (RCPs: CO_2,N_2O) ●	AR5 I-2, I-10, I-11, I-12
2	Global Mean Surface Air Temperature (GMST)	↑	****	*** ■	**** ●	AR5 I-2, I-10, I-11, I-12
3	GMST over all continents except Antarctica	↑	****	* ■	**** ●	AR5 I-2, I-10, I-11, I-12
4	Global mean sea level	↑	****	** ■	**** ●	AR5 I-3, I-10, I-13
5	Arctic sea ice cover	↓	****	** ■	** ●	AR5 I-4, I-10, I-11, I-12
6	Hot days and nights over land (warmth, frequency)	↑	**	** ■	**** ●	AR5 SPM-1
7	Cold days and nights over land (warmth, frequency)	↓	**	** ■	**** ●	AR5 SPM-1
8	Extreme high sea level (incidence, magnitude)	↑	* (since 1970)	X	** ●	AR5 SPM-1
9	Heat waves and warm spells over land (frequency, duration)	◇	*MC*	* ■	** ●	AR5 SPM-1
10	Heavy precipitation events	◇	*	*MC* ■	** ●	AR5 I-2, I-10, I-12
11	Drought (intensity, duration)	◇	*MC* (some regions)	*LC* ■	* ●	AR5 SPM-1, SREX-4
12	Tropical cyclones (intensity, frequency, some basins)	~	*LC*	*LC* ■	MC (intensity increase, some basins) ●	AR5 SPM-1
13	Global mean precipitation	↑	*LC*	*LC* ■	**** ●	AR5 I-2, I-10, I-11, I-12
14	Contrast between wet and dry regions	↑	X	X	HC ●	AR5 I-12
15	Snow cover (Northern Hemisphere, extent)	↓	HC	HC ■	HC ●	AR5 I-4, I-10, I-12
16	Permafrost regions (degrade)	↓	MC	X	MC ●	AR5 I-4, I-12
17	Storm tracks (shift poleward)	↑	*	X	* ●	AR5 I-2, I-12
18	Wave heights (different oceans)	↑	MC (N. Atlantic)	X	** (Arctic a) * (Southern b) ●	AR5 I-3, I-13
19	Upper ocean (warming)	↑	****	*** ■	*** ●	AR5 I-3, I-10, I-11, I-12
20	Ocean acidification	↑	****	*** ■	**** ●	AR5 I-3, I-10, I-6
21	Oceanic oxygen	↓	*MC*	*MC* ■	** ●	AR5 I-3, I-10, I-6
22	Floods (magnitude, frequency)	~	*LC*	*LC* ■	*LC* ●	SREX-3
23	Mountain phenomena (slope instabilities, mass movement, glacial lake outbursts)	↑	*HC*	*HC* ■	*HC* ●	SREX-3, AR4 SyR
24	Monsoons	~	*LC*	*LC* ■	*LC* ●	SREX-3
25	Plant and animal species (move poleward or up in altitude)	↑	*HC*	*HC* ■	*HC* ●	AR4 II-SPM, AR4-SyR
26	Mountain phenomena (slope instabilities, mass movement, glacial lake outbursts)	↑	*HC*	*HC* ■	*HC* ●	SREX-3, AR4 SyR
27	Timing of spring events (earlier leafing, greening, planting, bird migration, etc.)	↑	*HC*	*HC* ■	*HC* ●	AR4 SyR
28	Marine/freshwater biological systems (shifts in algal, plankton, and fish ranges)	~	*HC*	*HC* ■	*HC* ●	AR4 SyR
29	Human health (heat-related mortality, infectious disease vectors)	↑	*MC*	MC ■	X ●	AR4 SyR
30	Water resources	↓	X	X	*HC* (many regions) ●	AR4 SyR-SPM
31	Mountain glaciers	↓	*HC*	X	*HC* ●	AR4 II-SPM
32	Coral degradation, bleaching	↑	*HC*	–	*HC* ●	AR4 II-SPM, SyR-SPM
33	Economic losses from weather- and climate-related disasters	↑	*HC*	X	*HC* ●	SREX-4
34	Annual costs of climate change	↑	X	X	** ●	AR4 SyR-SPM

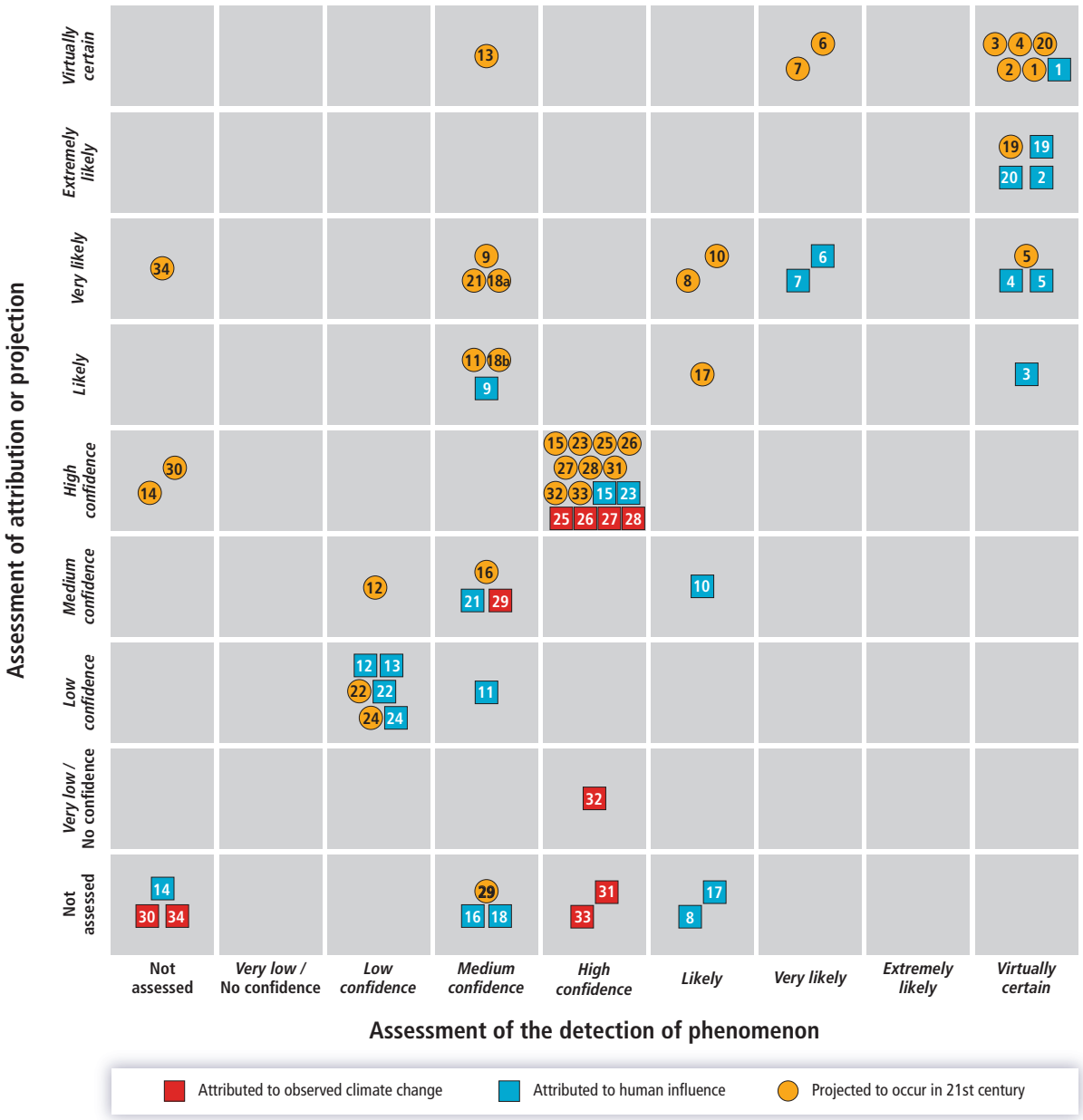


Figure 1-6 | Confidence in the attributed (squares) and projected 21st century (yellow circles) changes in climate system phenomena plotted as a function of confidence in their detection to date. Phenomena and sources (AR4, SREX, WGI AR5) are given in Table 1-2. Strength of confidence is sorted into the nine bins as noted on the axes (no assessment was made; a statement was made and assigned no formal confidence level or *very low confidence*; *low confidence*; *medium confidence; high confidence* (no quantification); or *likely; very likely; extremely likely; virtually certain*). Attribution is to either human influence (blue squares, as used by WGI) or observed local/regional climate change (red squares, as used by WGII). Projections assume global warming exceeding 2°C. For AR5 WGII results see, *inter alia*, Chapters 18 and 19.

attribution, or projection has been made across the Working Groups. A schematic presentation of this detection–attribution–projection sequence from preceding reports is given in Figure 1-6. For WGII AR5 attributions, see Chapter 18; and for projections, see the other chapters.

1.3.1. Special Report on Renewable Energy Sources and Climate Change Mitigation

SRREN (IPCC, 2011) assesses literature on the challenges of integrating renewable energy sources into existing energy sources to meet the goals of climate change mitigation and sustainable development. More specifically, it examines six renewable energy sources (bioenergy, direct solar energy, geothermal energy, hydropower, ocean energy, and wind energy) in terms of available technologies, technological potential, and associated costs. SRREN found that the deployment of renewable energy technologies has increased rapidly in recent years, often associated with cost reductions that are expected to continue with advancing technology. Despite the small contribution of renewable energy to current energy supplies, SRREN shows the global potential of renewable energy to be substantially higher than the global energy demand. It is therefore not the technological potential of renewable energy that constrains its development, but rather economic factors, system integration, infrastructure constraints, public acceptance, and sustainability concerns

Table 1-3 | Examples of linkages between the Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) and the AR5 WGII with chapter references in parentheses.

	SRREN findings	WGII AR5 findings
Water resources	Water availability limits the development of water cooled thermal power and hydropower. Environmental issues will continue to affect hydropower opportunities. (5.1, 5.6, 9.3)	Climate change is predicted to affect surface and groundwater supplies. Development of water-dependent energy resources can also affect freshwater ecosystems. (4.4, 19.3)
Ocean systems	Most ocean energy technologies are at the conceptual phase. Potential technologies include submarine turbines for tidal currents, ocean thermal energy conversion, and devices that harness energy of waves and salinity gradients. (6.2, 6.3, 6.5)	Offshore renewable energy introduces additional drivers of change for near- and offshore coastal and marine ecosystems and species. Ocean geoengineering approaches may have large environmental footprints. (5.5, 6.4)
Land cover changes	The sustainability of bioenergy (i.e., lifecycle GHG emissions) is influenced by land and biomass resource management practices. (2.2, 2,8, 9.3)	Land cover change associated with biofuel production has food security implications; related land use change can alter ecosystems, species, and carbon storage. (19.3, 19.4, 27.2)
Resilient pathways	Higher energy prices associated with transitions from fossil fuels to biofuels and other renewable energy sources may have adverse effects on socioeconomic development. (9.4, 10.5)	The challenge is to identify and implement mixes of technological options that reduce net carbon emissions and support sustained economic and social growth. (20.3)
Regional effects	Latin America is second to Africa for technical potential in producing bioenergy from rain-fed lignocellulosic feedstocks on unprotected grassland and woodlands. (2.2)	Bioenergy production requires large areas with risk of environmental degradation and may involve strong economic teleconnections (e.g., Latin America). (27.2, 27.3)
	The quantity of water resources availability in Central and South America is the largest in the world. The region has the largest proportion of electricity generated through hydropower facilities. (5.2)	Hydropower, the main source of renewable energy available in Central and South America, is prone to serious effects of climate change. Altered river flows affect development in this region and use of land for biofuel production. (27.3, 27.6, 27.8)

(IPCC, 2011). Several SRREN findings have clear linkages with this assessment of climate change impacts, adaptation, and vulnerability, as summarized in Table 1-3.

1.3.2. Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation

SREX (IPCC, 2012) is the first IPCC Special Report produced jointly by Working Groups I and II and is the first IPCC report focused specifically on risk management. The report integrates perspectives from historically distinct research communities studying climate science, climate impacts, extreme events and impacts, climate adaptation, and disaster risk management. It assesses relationships between climate change and the characteristics of extreme weather and climate events. SREX provides information on existing societal exposure and vulnerability to climate-related extreme events and disasters; observed trends in weather- and climate-related disasters, disaster losses, and in disaster risk management; projected changes in weather and climate extremes during the 21st century; approaches for managing the increasing risks of climate extremes and disasters; and implications for sustainable development. SREX Chapter 9 is devoted to 14 case studies that illustrate the impacts of extreme climate-related events and options for risk management and adaptation, such as early-warning systems, new forms of insurance coverage, and expansion of social safety nets.

1.3.2.1. Themes and Findings of Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation

The most relevant results of the SREX assessment follow. They are synthesized along these major themes: changing weather and climate-related extreme events, trends in disaster losses, and managing the risks of extreme events and disasters. Other examples of findings presented in SREX concerning the type, magnitude, and frequency of extreme weather and climate events are presented in Table 1-2 of this chapter.

- Based on observations since 1950 there is evidence of changes in some climate-related extremes. It is *very likely* that there has been an overall decrease in the number of cold days and nights, and increase in the number of warm days and nights, at the global scale (SREX SPM, Section 3.3.1, Table 3-2). It is *likely* that there has been an increase in extreme coastal high water events related to increases in mean sea level (SREX SPM, 3.5.3). It is *likely* that anthropogenic influences have led to warming of extreme daily minimum and maximum temperatures at the global scale (SREX SPM, Sections 3.2.2, 3.3.1, 3.3.2, 3.4.4, 3.5.3, Table 3-1).
- The models project substantial warming in temperature extremes by the end of the 21st century. It is *virtually certain* that increases in the frequency and magnitude of warm daily temperature extremes and decreases in cold extremes will occur in the 21st century at the global scale. It is *very likely* that the length, frequency, and/or intensity of warm spells or heat waves will increase over most land areas (SREX SPM, Sections 3.3.2, 3.3.4, Table 3-3, Figure 3-5).
- It is *likely* that the frequency of heavy precipitation will increase in the 21st century over many areas of the globe (SREX SPM, Sections 3.3.2, 3.4.4, Table 3-3, Figure 3-7).
- Economic losses from weather- and climate-related disasters have increased, but with large spatial and interannual variability (*high confidence*, based on *high agreement*, *medium evidence*) (SREX SPM, Sections 4.5.1, 4.5.3, 4.5.4). Trends in losses have been heavily influenced by increasing exposure of people and economic assets (*high confidence*) (SREX SPM, Section 4.5.3).
- Economic, including insured, disaster losses associated with weather, climate-related events, and geophysical events are higher in developed countries. Fatality rates and economic losses expressed as a proportion of GDP are higher in developing countries (*high confidence*). Deaths from natural disasters occur much more in developing countries. From 1970 to 2008, for example, more than 95% of deaths from natural disasters were in developing countries (SREX SPM, Sections 4.5.2, 4.5.4).
- Development practice, policy, and outcomes contribute to shaping disaster risks (*high confidence*): skewed development that may lead to environmental degradation, unplanned urbanization, failure of governance, or reduction of livelihood options result in increased

exposure and vulnerability to disasters (SREX SPM, Sections 1.1.2, 1.1.3, 2.2.2, 2.5).

- Post-disaster recovery and reconstruction provide an opportunity for reducing the risks posed by future weather- and climate-related disasters (*robust evidence*, *high agreement*) (SREX SPM, Sections 5.2.3, 8.4.1, 8.5.2).
- Socioeconomic, demographic, health-related differences, access to livelihoods, good governance, and entitlements are some of the factors that lead to inequalities between people and countries. Inequalities influence local coping and adaptive capacity and pose challenges for risk management systems from local to national levels (*high agreement*, *robust evidence*) (SREX SPM, Sections 5.5.1, 6.2, 6.3.2, 6.6).
- The incorporation of climate change adaptation and disaster risk management into local, national, and international development practices and policies could bring benefits (*medium evidence*, *high agreement*) (SREX SPM, Sections 5.4, 5.5, 5.6, 6.3.1, 6.3.2, 6.4.2, 6.6, 7.4).
- Combining local knowledge with scientific and technical expertise helps communities reduce their risk and adapt to climate change (*robust evidence*, *high agreement*). Risk management works best when tailored to local circumstances (SREX SPM, Section 5.4.4).
- Many measures for managing current and future risks have additional benefits, such as improving peoples' livelihoods, conserving biodiversity, and improving human well-being (*medium evidence*, *high agreement*) (SREX SPM, Section 6.3.1, Table 6-1).
- Many measures, when implemented effectively, make sense under a range of future climates. These "low regrets" measures include systems that warn people of impending disasters; changes in land use planning; sustainable land management; ecosystem management; improvements in health surveillance, water supplies, and drainage systems; development and enforcement of building codes; and better education and awareness (SREX SPM, Sections 5.3,1, 5.3.4.3, 6.3.1, 6.5.1, 6.5.2, 7.4.3, Case Studies 9.2.11, 9.2.14).
- An iterative process involving monitoring, research, evaluation, learning, and innovation can promote adaptive management and reduce disaster risk in the context of climate extremes (*robust evidence*, *high agreement*) (SREX SPM, Sections 8.6.3, 8.7).
- Actions ranging from incremental improvements in governance and technology to more transformational changes are essential for reducing risk from climate extremes (*robust evidence*, *high agreement*) (SREX SPM, Sections 8.6, 8.6.3, 8.7).

1.3.2.2. Advances in Conceptualizing Climate Change Vulnerability, Adaptation, and Risk Management in the Context of Human Development

SREX conceptual framing reflects the diversity of expert communities involved in the assessment. It links exposure and vulnerability with socioeconomic development pathways as determinants of impacts and disaster risk for both human society and natural ecosystems. It is important to note that SREX acknowledges the fundamental role that values and aspirations play in people's perception of risk, of change and causality, and of imagining present and future situations. This value-based approach is put to work as a tool for managing the risks of extreme events and disasters enabling the recognition that socioeconomic systems are in constant flux, and that there are many conflicting and contradictory values in play. The conceptual framing of the problem space offered by SREX (SREX Figure SPM 1-1) serves as a point of departure for many WGII AR5 chapters. Equally important is the conceptualization of a feasible solution space offered in SREX. The solution space is further refined in the WGII AR5 through emphasis on co-benefits of adaptation and mitigation and the further development of transformational change to enable climate resilient development.

1.3.3. Relevant Findings from IPCC Working Group I Fifth Assessment Report

This section is a WGII synthesis of the WGI AR5 report that focuses on topics relevant to WGII science.[5] The relevant WGI AR5 chapters and sections are denoted in parentheses. Where statements have *high confidence* or *likely* or better quantification, these qualifiers are dropped for readability. Likewise, many phrases are exact quotations but are not presented in quotes. An overall assessment of climate change over the last several decades from WGI is: Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. Human influence on the climate system is clear; it has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes (SPM).

Greenhouse gases and climate forcing. Human activities are the dominant cause of the observed increase in well mixed GHGs since 1750 and of the consequent increase in climate forcing. The GHGs and their forcing continued to increase since AR4 (2, 6, 8). Ozone and stratospheric water vapor also contribute to this forcing (8). Aerosols partially offset this forcing and dominate the uncertainty in determining total anthropogenic forcing of climate change (8). Total anthropogenic climate forcing is positive and has increased more rapidly since 1970 than during prior decades (8). Present-day (2011) abundances of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) exceed the range over the past 800,000 years found in ice cores (5, 6). Annual emission of CO_2 from fossil fuels and cement production was 9.5 GtC in 2011, 54% above the 1990 level (SPM). More than 20% of added CO_2 will remain in the atmosphere for longer than 1000 years (6). Anthropogenic land use change has increased the land surface albedo (a negative forcing) and has also affected climate through the hydrologic cycle, but these effects

[5] This narrative is taken primarily from the executive summaries of the WGI Final Draft chapters and reflects the WGI SPM approved on 27 September 2013 in Stockholm. For the most part, WGI findings summarized here have *high confidence* or a *likely* or better quantification, and hence the confidence and likelihood statements have been dropped for readability. All quantitative ranges are *likely* (66% confidence) or *very likely* (90% confidence) or the modeled range (where noted). In a few instances, assessments with *low confidence* are included and so noted. This WGII narrative is intended to be accurate, but for the purpose here the exact WGI language has been edited and concatenated where possible (e.g., 1950 is substituted for "the middle of the 20th century"). Although quotation marks are not used, there remain long phrases that are direct quotes from the WGI AR5 chapters. All numerical values are verbatim. For the level of uncertainty and the precise wording of the WGI assessment refer directly to the WGI approved SPM and the accepted chapters.

are more uncertain and difficult to quantify (8.3.5). Spatial gradients in forcing (i.e., aerosols, ozone, land use change) affect regional temperature responses (8). Cumulative CO_2 emissions from 1750 to 2011 are 365 GtC (fossil fuel and cement) plus 180 GtC (deforestation and other land use change) (SPM). This 545 GtC represents about half of the 1000 GtC total that can be emitted and still keep global warming under 2°C relative to the reference period 1861–1880 (SPM).

Air quality on continental scales. Future surface ozone (air pollution) decreases over most continents for RCP2.6, RCP4.5, and RCP6.0; but it increases for RCP8.5 due to rising CH_4 (11). Changes in air quality for the RCPs are driven primarily by pollutant emissions and secondarily by climate change (11). Air pollution is less under RCP scenarios than under SRES scenarios (11).

Surface Temperatures. Global mean surface temperature increased by 0.85°C (0.65°C to 1.06°C) over the period 1880–2012 (linear trend) (SPM) and by 0.72°C over the period 1951–2012 (2). Each of the last 3 decades (from 1983 to 2012) has been successively warmer than any preceding decade since 1850 (SPM). The decade 2003–2012 has been the warmest over the instrumental record, even though the rate of warming over 1998–2012 is smaller than the average rate since 1951 (0.05°C vs. 0.12°C per decade) (2). For the NH, the period 1983–2012 was the warmest of the last 1.400 kyr (5). The slower surface warming trend over the period 1998–2012 vs. 1951–2012 is due in roughly equal measure to a reduced trend in radiative forcing and a cooling contribution from internal, possibly oceanic variability (SPM). Models reproduce the overall 1951–2012 warming trend, but not the smaller trend for 1998–2012 (9). More than half of the 1951–2010 temperature increase is due to the observed anthropogenic increase in GHGs (10). The projected near term (2016–2035) mean surface temperature increase is 0.9°C to 1.3°C (11), and the long term (2081–2100) ranges from 0.9°C to 2.3°C (RCP2.6) to 3.2°C to 5.4°C (RCP8.5) (values are relative to 1850–1900, the earliest period for which global mean surface temperatures have been measured, and include the 0.6°C offset from that period to the model reference period 1986–2005) (SPM, 2, 12).

Global temperatures during the last interglacial period (about 120,000 years ago) were never more than 2°C higher than preindustrial levels (5). By 2050 the global warming range is 1.5°C to 2.3°C above the 1850–1900 period based on the range across all RCPs and models (11.3.6). Near the end of the century (2081–2100) warming above 4°C is typical of RCP8.5, while that of RCP2.6 remains below 2°C (12). Orbital forcing will not trigger widespread glaciation during the next 1000 years (5).

Climate models reproduce observed continental-scale mean surface temperature patterns; on sub-continental and smaller scales model capability is reduced, but is better than in AR4 (9). Regional downscaling provides climate information at the smaller scales needed for impact studies and adds value in regions with highly variable topography and for various small-scale phenomena (9). Anthropogenic warming in the 21st century will proceed more rapidly over land areas than over oceans, and the Arctic region is projected to warm the most (11, 12).

Precipitation. Observed trends in global land-average precipitation have *low confidence* prior to 1950 and *medium confidence* thereafter (2). Simulation of large-scale precipitation patterns has improved somewhat since AR4, but precipitation at regional scales is not well simulated (9). Precipitation (global annual averages) will increase as temperatures increase, and the contrast between dry and wet regions and that between wet and dry seasons will increase over most of the globe (12). By 2100 under RCP8.5, high latitudes will experience more precipitation; many moist mid latitude regions will also experience more; while many mid-latitude and subtropical arid and semi-arid regions will experience less (12). These patterns are also typical of near-term climate change (11). Trends will not be apparent in all regions, especially in the near term, because of natural variability and possible influences of aerosols and land use change (11).

Extreme temperatures and precipitation. Since 1950, the numbers of cold days/nights have decreased and the numbers of warm days/nights have increased globally (2); and model simulation of these extreme events has improved since AR4 (9). Since 1950, anthropogenic forcing has contributed to the observed changes in daily temperature extremes on the global scale (10). In most regions the frequency of warm days/nights will increase in the next decades, while that of cold days/nights will decrease (11). Increases in the frequency, duration, and magnitude of hot extremes along with heat stress are expected; however, occasional cold winter extremes will occur (12). Extreme high temperatures (20-year return values) are projected to increase at a rate similar to or greater than the rate of increase of summer mean temperatures in most regions (12). There is a *no confidence* level assigned to projected near-term increases in the duration, intensity, and spatial extent of heat waves and warm spells (11), but in the long term heat waves will occur at higher frequency and longer duration in response to increased seasonal mean temperatures (12.4.3). Since 1950, the frequency or intensity of heavy precipitation events has increased in North America and Europe (2, SPM). Trends in small-scale severe weather events (e.g., hail, thunderstorms) have *low confidence* (2). With global warming, the frequency and intensity of heavy/extreme precipitation events will increase over most mid-latitude land and over wet tropical regions (12), and extreme daily precipitation rates will increase faster than the mean time average (7). Most models underestimate the sensitivity of extreme precipitation to temperature variability/trends, and thus projections may underestimate these extremes (9).

Floods and droughts. In many regions, historical droughts (last 1000 years) and historical floods (last 500 years) have been more severe than those observed since 1900 (5). Global-scale trends in drought or dryness since 1950 have *low confidence* due to lack of direct observations, methodological uncertainties, and geographical inconsistencies; hence confidence levels in global drought trends since the 1970s as reported in AR4 are overstated (2). Regional trends are found: the frequency and intensity of drought has increased in the Mediterranean and West Africa, and it has decreased in central North America and northwest Australia since 1950 (2, 2.6.2.2). There is *low confidence* in attributing drought changes to human influence (10). Projected changes in soil moisture and surface runoff have low confidence in the near term (11), but by 2100 under RCP8.5, annual runoff will decrease in parts of southern Europe, Middle East, and southern Africa, and increase in high northern latitudes (12). Decreases in soil moisture with increased risk of agricultural drought are projected in presently dry regions (12).

Tropical cyclones, storms, and wave heights. Observed changes in tropical cyclone activity on a centennial scale as well as attribution to human influence have *low confidence* (2, 10); however, the frequency and intensity of the strongest tropical cyclones in the North Atlantic have increased since the 1970s (2). In a few studies, high-resolution atmospheric models have reproduced the year-to-year variability of Atlantic hurricane counts (9). Future changes in intensity and frequency of tropical cyclones will vary by region, but basin-specific projections have *low confidence* (11, 14). The maximum wind speed and precipitation rates of tropical cyclones will increase (14).

Atmospheric circulation features have moved poleward since the 1970s, including a poleward shift of storm tracks and jet streams (2), and model simulation of these patterns has improved since AR4 (9). Large-scale trends in storminess over the last century have *low confidence* (2, 2.6.4). Projections of the position and strength of NH storm tracks, especially for the North Atlantic basin, have *low confidence* (11, 12, 14). With global warming, a shift to more intense individual storms and fewer weak storms is projected (12).

Mean significant wave height has increased over much of the Atlantic Ocean north of 45°N since 1950, with winter season trends of up to 20 cm per decade (*medium confidence*) (3, 3.4.5). Wave heights and the duration of the wave season will increase in the Arctic Ocean as a result of reduced sea ice extent (13). Wave heights will increase in the Southern Ocean as a result of enhanced wind speeds (13).

Ocean warming, stratification, and circulation. Overall, the ocean has warmed throughout most of its depth over some periods since 1950, and this warming accounts for about 93% of the increase in the Earth's energy inventory between 1971 and 2010 (3). The upper ocean above 700 m has warmed from 1971 to 2010, and the thermal stratification has increased by about 4% above 200 m depth (3). Anthropogenic forcings have made a substantial contribution this upper ocean warming (10). Measurement errors in the temperature data sets have been corrected since the AR4 (10). The global ocean continues to warm in all RCP scenarios (11, 12). To date there is no observational evidence of a long-term trend in Atlantic Meridional Overturning Circulation (3); and over the 21st century it is projected to weaken but not undergo an abrupt transition or collapse (12).

Ocean acidification and low oxygen. Oceanic uptake of anthropogenic CO_2 results in gradual acidification of the ocean (3). Since 1750 the pH of seawater has decreased by 0.1 (a 26% increase in hydrogen ion concentration) (3). Increased storage of carbon by the oceans over the 21st century will increase acidification, decreasing pH further by 0.065 for RCP2.6 and 0.31 for RCP8.5 (6). Aragonite under-saturation becomes widespread in parts of the Arctic and Southern Oceans and in some coastal upwelling systems at atmospheric CO_2 levels of 500 to 600 ppm (6). Oxygen concentrations have decreased since the 1960s in the open ocean thermocline of many regions (*medium confidence*) (3). By 2100, the oxygen content of the ocean will decrease by a few percent (6). There is no consensus on projection of the very low oxygen (hypoxic or suboxic) waters in the open ocean (6).

Sea ice. Continuing the trends reported in AR4, the annual Arctic sea ice extent decreased at rate of 3.5 to 4.1% per decade between 1979 and 2012 (4). Over the past 3 decades, Arctic summer sea ice retreat was unprecedented and Arctic sea surface temperatures were anomalously high, compared with the last 1450 years (SPM). The Arctic average winter sea ice thickness decreased between 1980 and 2008 (4). Current climate models reproduce the seasonal cycle and downward trend of Arctic sea ice extent (9). Anthropogenic forcings have contributed to Arctic sea ice loss since 1979 (10). With global warming, further shrinking and thinning of Arctic sea ice cover is projected, and the Arctic Ocean will be nearly ice free in September before 2050 for the high-warming scenarios like RCP8.5 (11, 12). There is little evidence in climate models of an Arctic Ocean tipping point, that is, the transition from a perennially ice covered to a seasonally ice-free expanse beyond which further sea ice loss is unstoppable and irreversible (12). Annual Antarctic sea ice extent increased by 1.2 to 1.8% per decade between 1979 and 2012 (4). The scientific understanding of this observed increase has *low confidence* (10). With global warming, Antarctic sea ice extent and volume is expected to decrease (*low confidence*) (12).

Ice sheets, glaciers, snow cover, and permafrost. During periods over the past few million years that were globally warmer than present, the Greenland and West Antarctic ice sheets were smaller (5). The Antarctic and Greenland ice sheets have on average lost ice during the last 2 decades, and the rate of loss has increased over the most recent decade to a sea level rise equivalent of 0.6 mm yr^{-1} for Greenland and 0.4 mm yr^{-1} for Antarctica (4). Anthropogenic influences have contributed to Greenland ice loss since 1990 and to the retreat of glaciers since the 1960s, but there is *low confidence* in attributing the causes of Antarctic ice loss (10). With global warming, model studies agree that the Greenland ice sheet will significantly decrease in area and volume, while the Antarctic ice sheet increases in most projections (*confidence* not assessed) (12, 13.4.4). Global warming above a certain threshold (e.g., 2°C to 4°C above the 1850–1900 period) would lead to the near-complete loss of the Greenland Ice Sheet over a millennium or more (*confidence* not assessed) (13). There is *low confidence* and little consensus on the likelihood of abrupt or nonlinear changes in components of the climate system over the 21st century (12).

Multiple lines of evidence support very substantial Arctic warming since the mid-20th century (SPM). Almost all glaciers world-wide have continued to shrink since AR4 (4). Over the last decade, most ice was lost from glaciers in the Canadian Arctic, Greenland ice sheet periphery, Southern Andes, Asian Mountains, and Alaska (4). Current glacier extents are out of balance with current climate, and glaciers will continue to shrink even without further warming (4). Snow cover extent has decreased in the NH, particularly in spring (4); and reductions since 1970 have an anthropogenic component (10). Permafrost temperatures have increased in most regions since the early 1980s: observed warming was up to 3°C in parts of Northern Alaska and 2°C in parts of the Russian European North (4, SPM). With global warming, NH snow cover extent and permafrost extent will decrease further (11, 12). By 2100 the decrease in near-surface permafrost area ranges from 37% (RCP2.6) to 81% (RCP8.5) (*medium confidence*) (12).

Sea level rise. During the last interglacial period, when global mean temperatures were no more than 2°C above pre-industrial values (*medium confidence*), maximum global mean sea level was, for several thousand years, 5 m to 10 m higher than present (SPM, 5, 5.3.4, 5.6.1,

5.6.2, 13, 13.2.1) with substantial contributions from Greenland and Antarctic Ice Sheets (5, 13). The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous 2 millennia (SPM). Global mean sea level has risen at an average rate of 1.7 mm yr^{-1} from 1901 to 2010 and at a faster rate, 3.2 mm yr^{-1}, from 1993 to 2010 (3). There is a substantial anthropogenic contribution to the global mean sea level rise since the 1970s (10). The rate of global mean sea level rise during the 21st century will exceed that observed during 1971–2010 for all RCP scenarios (13). For the period 2081–2100 compared to 1986–2005, process-based models project a global mean sea level rise ranging from 0.26 to 0.55 m (RCP2.6) up to 0.45 to 0.82 m (RCP8.5) (13). By 2100 for RCP8.5, this rise is 0.52 to 0.98 m, with a rate of rise reaching 8 to 16 mm yr^{-1} (SPM, 13). Only collapse of marine-based sectors of the Antarctic ice sheet could cause global mean sea level to rise substantially above these projections, probably not exceeding several tenths of a meter (*medium confidence*) by 2100 (13). Semi-empirical projections of 2100 sea level rise have a wide spread across models, some overlapping with the process-based models and some twice as large; however, there is *low confidence* in these projections (13, 13.5.2, 13.5.3). If global warming exceeds a certain threshold resulting in near-complete loss of the Greenland Ice Sheet over a millennium or more (*confidence* not assessed), global mean sea level would rise about 7 m (13). Future sea level change will vary regionally, but about 70% of the global coastlines are projected to experience a sea level change within 20% of the global mean (13).

The magnitude of extreme high sea level events has increased since 1970 (3). Future sea level extremes will become more frequent beyond 2050, primarily as a result of increasing mean sea level (13). By 2100 the frequency of current sea level extremes will increase by large factors in some regions (13, 13.7.2). Region-specific projections of storminess and associated storm surges have low confidence (13).

Climate patterns. The El Niño-Southern Oscillation (ENSO) system has remained highly variable throughout the past 7000 years with no discernible evidence of orbital modulation (5). The observed variability of the ENSO in the tropical Pacific is now reproduced in most climate models (9). Models project an eastward shift in the ENSO teleconnection patterns of temperature and precipitation variations over the North Pacific and North America (14). ENSO remains the dominant mode of interannual climate variability in the future, and the ENSO precipitation anomalies will intensify due to increased moisture (14). Aggregated over all monsoon systems and over the 21st century, the monsoon will increase in area and intensity while its circulation weakens (14). Monsoon onset dates become earlier or do not change and monsoon retreat dates delay, lengthening the monsoon season (14). Reduced warming and decreased precipitation is projected in the eastern tropical Indian Ocean, with increased warming and precipitation in the western, influencing East Africa and Southeast Asia precipitation (14).

1.3.4. Relevant Findings from IPCC Working Group III Fifth Assessment Report

The WGIII report assesses scientific research related to the mitigation of climate change. Because mitigation lowers the effects of climate change as well as the risks of extreme impacts, it is part of a broader policy strategy that includes adaptation to climate impacts. Both mitigation (WGIII) and adaptation (WGII) involve risk management in the context of many prevailing uncertainties. Uncertainties arise not only in the natural but also in human and social systems, including responses of these to policy interventions. It is possible that extreme climate impacts could play a central role in determining the level of mitigation, adaptation, and other policy responses to climate change (WGIII AR5 Chapter 2).

Over the last two WGIII assessment reports, one of the most important shifts in the scientific literature reflects underlying changes in the structure of the world economy: the underlying determinants of emissions—such as technologies, investment patterns, resource use, lifestyles, and development pathways in general—have not substantially shifted toward a low-GHG pattern despite the adoption of the UNFCCC and the Kyoto Protocol. In 2010, GHG emissions surpassed 50 Gt CO_2-eq (13.6 GtC), higher than in any previous year since 1750. Most of the emission growth between 2000 and 2010 came from fossil-fuel use in the energy and industry sectors, and took place in emerging economies. This emission growth was not met by significant GHG emission cuts in the industrialized country group, which continued to dominate historical long-term contributions to global CO_2 emissions. In 2010, median per capita GHG emissions in high-income countries were roughly 10 times higher than in low-income countries (WGIII AR5 Chapters 1, 5).

One of the central messages of WGIII AR5 is that technological and behavioral options exist that would allow the world's economies to follow pathways to much lower future emissions of GHGs. Since AR4 a substantial scenario literature has emerged on the technological, economic, and institutional conditions needed to achieve different long-term pathways leading to a stabilization of atmospheric GHG concentrations in 2100. A continuation of current trends of technological change in the absence of explicit climate change mitigation policies is not sufficient to bring about stabilization of GHGs. Scenarios that are *more likely than not* to limit temperature increase to 2°C are becoming increasingly challenging, and most of these include a temporary overshoot of this concentration goal requiring net negative CO_2 emissions after 2050 and thus large-scale application of carbon dioxide removal (CDR) technologies (WGIII AR5 Chapter 6). CDR methods are not mature and have biogeochemical and technological limitations to their potential on a global scale and carry side effects and long-term consequences on a global scale (WGI AR5 SPM; WGIII AR5 Chapter 6). The increasing dependence of pathways on CDR options reduces the ability of policymakers to hedge risks freely across the mitigation technology portfolio (WGIII AR5 Chapter 6). The literature highlights the importance of a systemic, cross-sectoral approach to mitigation. Approaches that emphasize only a subset of sectors or a subset of actions may miss synergies between sectors, raise the costs of mitigation, cause unexpected consequences, and prove insufficient to meet long-term mitigation goals (WGIII AR5 Chapters 6 to 11). The costs of mitigation grow over-proportionally with the stringency of the stabilization target. Delays in mitigation and the unavailability of individual mitigation technologies increase the cost of mitigation and negatively affect the probability of meeting ambitious long-term atmospheric stabilization goals (WGIII AR5 Chapter 6).

Mitigation policies involve multiple actors and institutions at the international, regional, national, and sub-national scales—from global

treaties to firms and individual households. Since AR4 a body of literature has been emerging to explain how this multiplicity of actors and levels, focused on a multiplicity of interacting goals, affects the design and evolution of mitigation policy (WGIII AR5 Chapters 13, 14, 15). Approaches to international cooperation in climate policies have increased and become more diverse ranging from strong multi-lateralism to harmonized national and regional policies (WGIII AR5 Chapter 13). Linkages among regional, national, and sub-national programs may complement international cooperation. Carbon markets have been the focus of regional policy due, in part, to the greater opportunities for trade as carbon markets expand (WGIII AR5 Chapters 13, 14). A combination of policies that address providing a price signal, removing barriers, and promoting long-term investments could be most effective. If there is no coordination within an integrated perspective then results in one area may be counteracted by results in another area, for instance through leakage and rebound effects (WGIII AR5 Chapter 15).

While mitigation efforts generate costs and trade-offs, they also offer possible synergies because many of the policies that can mitigate GHGs also help address other policy goals, such as managing air pollution, water scarcity, or energy security. Since AR4 a substantial literature has emerged on this topic, underscoring the link of mitigation to a wide range of societal goals, often designated as sustainable development (WGIII AR5 Chapters 3, 4, 15).

References

Alcaide, G.G., J.C.V. Zurián, and R.A. Benavent, 2012: Análisis del proceso de internacionalización de la investigación española en ciencia y tecnología (1980-2007). *Revista Espanola de Documentacion Cientifica*, **35**, 94-118.

Alston, M., 2011: Gender and climate change in Australia. *Journal of Sociology*, **47(1)**, 53-70.

Arnell, N., T. Kram, T.R. Carter, K.L. Ebi, J.A. Edmonds, S. Hallegatte, E. Kriegler, R. Mathur, B. O'Neill, K. Riahi, H. Winkler, D.P. van Vuuren, and T. Zwickel, 2011: *A Framework for a New Generation of Socioeconomic Scenarios for Climate Change Impact, Adaptation, Vulnerability and Mitigation Research.* Primary background document for the workshop, "The Nature and Use of New Socioeconomic Pathways for Climate Change Research," Nov. 2-4, 2011, hosted by the Integrated Science Program, National Center for Atmospheric Research (NCAR), Mesa Laboratory, Boulder, CO, USA, 42 pp., www.isp.ucar.edu/sites/default/files/Scenario_FrameworkPaper_15aug11_1.pdf.

Arnold, D.G. (ed.), 2011: *The Ethics of Global Climate Change.* Cambridge University Press, Cambridge, UK and New York, NY, USA, 354 pp.

Barnett, J. and S. O'Neill, 2010: Maladaptation. *Global Environmental Change*, **20(2)**, 211-213.

Borras, S.M., P. McMichael, and I. Scoones (eds.), 2011: *The Politics of Biofuels, Land and Agrarian Change.* Routledge, London, UK, 408 pp.

Boyd, E. and S. Juhola, 2009: Stepping up to the climate change: opportunities in re-conceptualising development futures. *Journal of International Development*, **21(6)**, 792-804.

Brooks, N., N. Grist, and K. Brown, 2009: Development futures in the context of climate change: challenging the present and learning from the past. *Development Policy Review*, **27(6)**, 741-765.

Brown, A., 2012: Atmospheric science: global implications for Africa. *Nature Climate Change*, **2**, 769, doi:10.1038/nclimate1736.

Büscher, B., S. Sian, K. Neves, J. Igoe, and D. Brockington, 2012: Towards a synthesized critique of neoliberal biodiversity conservation. *Capitalism Nature Socialism*, **23(1)**, 4-30.

Caney, S., 2012: Just emissions. *Philosophy & Public Affairs*, **40**, 255-300.

Gagnon-Lebrun, F. and S. Agrawala, 2006: *Progress on Adaptation to Climate Change in Developed Countries: An Analysis of Broad Trends.* ENV/EPOC/GSP(2006)1/FINAL, The Organisation for Economic Co-operation and Development (OECD), Paris, France, 63 pp.

Gardiner, S.M. (ed.), 2011: *A Perfect Moral Storm: The Ethical Tragedy of Climate Change.* Oxford University Press, Inc., New York, NY, USA, 512 pp.

Gingras, Y. and S. Mosbah-Natanson, 2010: Les sciences sociales françaises entre ancrage local et visibilité international. *European Journal of Sociology*, **51**, 305-321.

Grist, N., 2008: Positioning climate change in sustainable development discourse. *Journal of International Development*, **20(6)**, 783-803.

Gupta, J., C. Termeer, J. Klostermann, S. Meijerink, M. van den Brink, P. Jong, S. Nooteboom, and E. Bergsma, 2010: The adaptive capacity wheel: a method to assess the inherent characteristics of institutions to enable the adaptive capacity of society. *Environmental Science & Policy*, **13(6)**, 459-471.

Gutiérrez, M.E. and T. Espinosa, 2010: *Vulnerabilidad y Adaptación al Cambio Climático: Diagnóstico Inicial, Avances, Vacíos y Potenciales Líneas de Acción en Mesoamérica.* Notas Técnicas No. IDB-TN-144, Banco Interamericano de Desarrollo, Washington, DC, USA, 84 pp.

Heltberg, R., P.B. Siegel, and S.L. Jorgensen, 2009: Addressing human vulnerability to climate change: toward a 'no-regrets' approach. *Global Environmental Change*, **19(1)**, 89-99.

IPCC, 1990: *Climate Change: The IPCC Scientific Assessment. Report Prepared for IPCC by Working Group I* [Houghton, J.T., G.J. Jenkins, and J.J. Ephraums (eds.)]. Cambridge University Press, Cambridge, UK, New York, NY, USA, and Melbourne, Australia, 410 pp.

IPCC, 1992: *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment. Report Prepared for Intergovernmental Panel on Climate Change by Working Group I combined with Supporting Scientific Material* [Houghton, J.T., B.A. Calandar, and S.K. Varney (eds.)]. Cambridge University Press, Cambridge, UK, New York, NY, USA, and Victoria, Australia, 200 pp.

IPCC, 1996: *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change* [Watson, R.T., M.C. Zinyowera, and R.H. Moss (eds.)]. Cambridge University Press, Cambridge, UK, New York, NY, USA, and Melbourne, Australia, 889 pp.

IPCC, 2001a: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 881pp.

IPCC, 2001b: *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [McCarthy, J.J., O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1042 pp.

IPCC, 2005: *Guidance Notes for Lead Authors of the IPCC Fourth Assessment Report on Addressing Uncertainties.* Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, 4 pp.

IPCC, 2007a: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M.C. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1008 pp.

IPCC, 2007b: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 992 pp.

IPCC, 2007c: Summary for policymakers. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 7-22.

IPCC, 2007d: *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [Core Writing Team, Pachauri, R.K. and A. Reisinger (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

IPCC, 2011: *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Prepared by Working Group III of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, and C. von Stechow (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1075 pp.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp.

ISSC and UNESCO, 2013: *World Social Science Report 2013: Changing Global Environments.* International Social Science Council (ISSC) and the United Nations Educational, Scientific and Cultural Organization (UNESCO), OECD Publishing and UNESCO Publishing, Paris, France, 612 pp.

Jerneck, A. and L. Olsson, 2008: Adaptation and the poor: development, resilience and transition. *Climate Policy*, **8(2)**, 170-182.

Kates, R.W., W.R. Travis, and T.J. Wilbanks, 2012: Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences of the United States of America*, **109(19)**, 7156-7161.

Kirchik, O., Y. Gingras, and V. Larivière, 2012: Changes in publication languages and citation practices and their effect on the scientific impact of Russian science (1993-2010). *Journal of the American Society for Information Science and Technology*, **63(7),** 1411-1419.

Kriegler, E., B.C. O'Neill, S. Hallegatte, T. Kram, R.J. Lempert, R.H. Moss, and T. Wilbanks, 2012: The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathways. *Global Environmental Change*, **24(4)**, 807-822.

Liverman, D.M., 2010: Carbon offsets, the CDM and sustainable development. In: *Global Sustainability – A Nobel Cause* [Schellnhuber, H.J., M. Molina, N. Stern, V. Huber, and S. Kadner (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 129-141.

Marino, E. and J. Ribot, 2012: Special issue introduction: adding insult to injury: climate change, social stratification, and the inequities of intervention. *Global Environmental Change*, **22(2)**, 323-328.

Mastrandrea, M.D. and K.J. Mach, 2011: Treatment of uncertainties in IPCC Assessment Reports: past approaches and considerations for the Fifth Assessment Report. *Climatic Change*, **108(4)**, 659-673.

Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Frame, H. Held, E. Kriegler, K.J. Mach, P.R. Matschoss, G.-. Plattner, G.W. Yohe, and F.W. Zwiers, 2010: *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties.* Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, 5 pp.

McMichael, P., 2009: Contemporary contradictions of the Global Development Project: geopolitics, global ecology and the 'development climate'. *Third World Quarterly*, **30(1)**, 247-262.

Mearns, R. and A. Norton (eds.), 2010: *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World.* New Frontiers of Social Policy 52097, The World Bank, Washington DC, USA, 348 pp.

Meinshausen, M., S.J. Smith, K. Calvin, J.S. Daniel, M.L.T. Kainuma, J. Lamarque, K. Matsumoto, S.A. Montzka, S.C.B. Raper, K. Riahi, A. Thomson, G.J.M. Velders, and D.P.P. van Vuuren, 2011: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change*, **109(1)**, 213-241.

Moss, R.H. and S.H. Schneider, 2000: Uncertainties in the IPCC TAR: recommendations to lead authors for more consistent assessment and reporting. In: *Guidance Papers on the Cross Cutting Issues of the Third Assessment Report of the IPCC* [Pachauri, R., T. Taniguchi, and K. Tanaka (eds.)]. IPCC, Geneva, Switzerland, pp. 33-51.

Moss, R.H., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren, T.R. Carter, S. Emori, M. Kainuma, T. Kram, G.A. Meehl, J.F.B. Mitchell, N. Nakicenovic, K. Riahi, S.J. Smith, R.J. Stouffer, A.M. Thomson, J.P. Weyant, and T.J. Wilbanks, 2010: A new paradigm for the next generation of climate change scenarios. *Nature*, **463**, 747-756.

Nakicenovic, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grubler, T.Y. Jung, T. Kram, E.L. La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H.M. Pitcher, L. Price, K. Riahi, A. Roehrl, H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S.J. Smith, R. Swart, S. van Rooijen, N. Victor, and Z. Dadi, 2000: *Emissions Scenarios: A Special Report of the Intergovernmental Panel on Climate Change* [Nakicenovic, N. and R. Swart (eds.)]. Cambridge University Press, UK, 570 pp.

New, M., D. Liverman, H. Schroeder, and K. Anderson, 2010: Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications. *Philosophical Transactions of the Royal Society A*, **369**, 6-19.

O'Brien, K., 2013: Global environmental change III: closing the gap between knowledge and action. *Progress in Human Geography*, **37(4)**, 587-596.

O'Brien, K., A.L. St. Clair, and B. Kristoffersen (eds.), 2010: *Climate Change, Ethics and Human Security.* Cambridge University Press, Cambridge, UK, 246 pp.

O'Neill, B.C., T.R. Carter, K.L. Ebi, J. Edmonds, S. Hallegatte, E. Kemp-Benedict, E. Kriegler, L. Mearns, R. Moss, K. Riahi, B. van Ruijven, , and D. van Vuuren, 2012: *Meeting Report of the Workshop on the Nature and Use of New Socioeconomic Pathways for Climate Change Research.* Workshop hosted by the Integrated Science Program, National Center for Atmospheric Research (NCAR), Mesa Laboratory, Nov. 2-4, 2011, Boulder, CO, USA, www.isp.ucar.edu/sites/default/files/Boulder%20Workshop%20Report_0.pdf.

OECD, 2013: *OECD Policy Guidance on Integrating Climate Change Adaptation into Development Co-Operation.* Organization for Economic Co-operation and Development (OECD), Paris, France.

Ogallo, L., 2010: The mainstreaming of climate change and variability information into planning and policy development for Africa. *Procedia Environmental Sciences*, **1**, 405-410.

Park, S., M. Howden, and S. Crimp, 2012: Informing regional level policy development and actions for increased adaptive capacity in rural livelihoods. *Environmental Science & Policy*, **15(1)**, 23-37.

Parson, E., V. Burkett, K. Fisher-Vanden, D. Keith, L. Mearns, H. Pitcher, C. Rosenzweig, and M. Webster, 2007: *Global Change Scenarios: Their Development and Use.* Synthesis and Assessment Product 2.1B of the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, US Department of Energy Publications, Paper 7, Washington, DC, USA, 106 pp.

Pelling, M., 2010: *Adaptation to Climate Change: From Resilience to Transformation.* Routledge, Oxford, UK, 224 pp.

Pogge, T., 2008: *World Poverty and Human Rights: Cosmopolitan Responsibilities and Reforms.* 2nd edn., Polity Publishing, Malden, MA, USA, 352 pp.

Richardson, K., W. Steffen, and D. Liverman, 2011: *Climate Change: Global Risks, Challenges and Decisions.* Cambridge University Press, Cambridge, UK, 524 pp.

Rosenzweig, C., G. Casassa, D.J. Karoly, A. Imeson, C. Liu, A. Menzel, S. Rawlins, T.L. Root, B. Seguin, and P. Tryjanowski, 2007: Assessment of observed changes and responses in natural and managed systems. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 79-131.

Schipper, E.L.F., 2007: *Climate Change Adaptation and Development: Exploring the Linkages.* Tyndall Centre for Climate Change Research Working Paper No.107, 20 pp., www.preventionweb.net/files/7782_twp107.pdf.

Stafford Smith, M., L. Horrocks, A. Harvey, and C. Hamilton, 2011: Rethinking adaptation for a 4°C world. *Philosophical Transactions of the Royal Society A*, **369**, 196-216.

Swart, R., L. Bernstein, M. Ha-Duong, and A. Petersen, 2009: Agreeing to disagree: uncertainty management in assessing climate change, impacts and responses by the IPCC. *Climatic Change*, **92(1-2)**, 1-29.

Timmons, R.J. and B.C. Parks (eds.), 2007: *A Climate of Injustice: Global Inequality, North-South Politics, and Climate Policy.* MIT Press, Cambridge, MA, USA, 418 pp.

Turner, B.L., 2010: Vulnerability and resilience: coalescing or paralleling approaches for sustainability science? *Global Environmental Change*, **20**, 570-576.

UN, 1993: *Agenda 21: Earth Summit – The United Nations Programme of Action from Rio.* United Nations, Department of Public Information, New York, NY, USA, 300 pp.

UN, 2003: *Report of the International Ministerial Conference of Landlocked and Transit Developing Countries and Donor Countries and International Financial and Development Institutions on Transit Transport Cooperation.* A/CONF.202/, United Nations Publications, New York, NY, USA, 27 pp., unctad.org/en/docs/aconf202d3_en.pdf.

UN DESA, 2008: *Handbook on the Least Developed Country Category: Inclusion, and Graduation and Special Support Measures*. United Nations Publications, New York, NY, USA, 98 pp.

UN DESA, 2012: *Statistical Yearbook 2010: Fifty-fifth Issue*. United Nations Publications, New York, NY, USA, 650 pp.

UN DESA, 2013: *World Economic Situation and Prospects 2013*. United Nations Publications, New York, NY, USA, 206 pp.

UNDP, 2007: *Human Development Report 2007/2008. Fighting Climate Change: Human Solidarity in a Divided World.* United Nations Development Programme (UNDP), Palgrave Macmillan, New York, NY, USA, 384 pp.

UNDP, 2011: *Human Development Report 2011. Sustainability and Equity: A Better Future for All.* United Nations Development Programme (UNDP), Palgrave Macmillan, New York, NY, USA, 185 pp.

UNDP, 2013: *Human Development Report 2013. The Rise of the South: Human Progress in a Diverse World.* United Nations Development Programme (UNDP), New York, NY, USA, 202 pp.

USAID, 2008: *Integrating Climate Change into Development.* US Agency for International Development (USAID), Washington, DC, USA, 12 pp.

van Vuuren, D.P., J.A. Edmonds, M. Kainuma, K. Riahi, and J. Weyant, 2011: A special issue on the RCPs. *Climatic Change*, **109(1)**, 1-4.

World Bank, 2010: *World Development Report 2010: Development and Climate Change.* The International Bank for Reconstruction and Development / The World Bank, Washington DC, USA, 439 pp.

World Bank, 2012: *Turn Down the Heat. Why a 4°C Warmer World Must Be Avoided.* A Report for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 106 pp.

World Bank, 2013: *World Development Indicators 2013.* The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 123 pp.

2 Foundations for Decision Making

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This chapter should be cited as:
Jones, R.N., A. Patwardhan, S.J. Cohen, S. Dessai, A. Lammel, R.J. Lempert, M.M.Q. Mirza, and H. von Storch, 2014: Foundations for decision making. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 195-228.

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Executive Summary

Decision support for impacts, adaptation, and vulnerability is expanding from science-driven linear methods to a wide range of methods drawing from many disciplines (*robust evidence*, *high agreement*). This chapter introduces new material from disciplines including behavioral science, ethics, and cultural and organizational theory, thus providing a broader perspective on climate change decision making. Previous assessment methods and policy advice have been framed by the assumption that better science will lead to better decisions. Extensive evidence from the decision sciences shows that while good scientific and technical information is necessary, it is not sufficient, and decisions require context-appropriate decision-support processes and tools (*robust evidence*, *high agreement*). There now exists a sufficiently rich set of available methods, tools, and processes to support effective climate impact, adaptation, and vulnerability (CIAV) decisions in a wide range of contexts (*medium evidence*, *medium agreement*), although they may not always be appropriately combined or readily accessible to decision makers. {2.1.1, 2.1.2, 2.1.3, 2.3}

Risk management provides a useful framework for most climate change decision making. Iterative risk management is most suitable in situations characterized by large uncertainties, long time frames, the potential for learning over time, and the influence of both climate as well as other socioeconomic and biophysical changes (*robust evidence*, *high agreement*). Complex decision-making contexts will ideally apply a broad definition of risk, address and manage relevant perceived risks, and assess the risks of a broad range of plausible future outcomes and alternative risk management actions (*robust evidence*, *medium agreement*). The resulting challenge is for people and organizations to apply CIAV decision-making processes in ways that address their specific aims. {2.1.2, 2.2.1, 2.3, 2.4.3}

Decision support is situated at the intersection of data provision, expert knowledge, and human decision making at a range of scales from the individual to the organization and institution. Decision support is defined as a set of processes intended to create the conditions for the production of decision-relevant information and its appropriate use. Such support is most effective when it is context-sensitive, taking account of the diversity of different types of decisions, decision processes, and constituencies (*robust evidence*, *high agreement*). Boundary organizations, including climate services, play an important role in climate change knowledge transfer and communication, including translation, engagement, and knowledge exchange (*medium evidence*, *high agreement*). {2.1.3, 2.2.1, 2.2, 2.3, 2.4.1, 2.4.2, 2.4.3}

Scenarios are a key tool for addressing uncertainty (*robust evidence*, *high agreement*). They can be divided into those that explore how futures may unfold under various drivers (problem exploration) and those that test how various interventions may play out (solution exploration). Historically, most scenarios used for CIAV assessments have been of the former type, though the latter are becoming more prevalent (*medium evidence*, *high agreement*). The new RCP scenario process can address both problem and solution framing in ways that previous IPCC scenarios have not been able to (*limited evidence*, *medium agreement*). {2.2.1.3, 2.3.2}

CIAV decision making involves ethical judgments expressed at a range of institutional scales; the resulting ethical judgements are a key part of risk governance (*robust evidence*, *medium agreement*). Recognition of local and indigenous knowledge and diverse stakeholder interests, values, and expectations is fundamental to building trust within decision-making processes (*robust evidence*, *high agreement*). {2.2.1.1, 2.2.1.2, 2.2.1.3, 2.2.1.4, 2.4, 2.4.1}

Climate services aim to make knowledge about climate accessible to a wide range of decision makers. In doing so they have to consider information supply, competing sources of knowledge, and user demand. Knowledge transfer is a negotiated process that takes a variety of cultural values, orientations, and alternative forms of knowledge into account (*medium evidence*, *high agreement*). {2.4.1, 2.4.2}

Climate change response can be linked with sustainable development through actions that enhance resilience, the capacity to change in order to maintain the same identity while also maintaining the capacity to adapt, learn, and transform. Mainstreamed adaptation, disaster risk management, and new types of governance and institutional arrangements are being studied for their potential to support the goal of enhanced resilience (*medium evidence*, *high agreement*). {2.5.2}

Transformational adaptation may be required if incremental adaptation proves insufficient (*medium evidence*, *high agreement*). This process may require changes in existing social structures, institutions, and values, which can be facilitated by iterative risk management and triple-loop learning that considers a situation and its drivers, along with the underlying frames and values that provide the situation context. {2.1.2, 2.5.3}

2.1. Introduction and Key Concepts

This chapter addresses the foundations of decision making with respect to climate impact, adaptation, and vulnerability (CIAV). The Fourth Assessment Report (AR4) summarized methods for assessing CIAV (Carter et al., 2007), which we build on by surveying the broader literature relevant for decision making.

Decision making under climate change has largely been modeled on the scientific understanding of the cause-and-effect process whereby increasing greenhouse gas emissions cause climate change, resulting in changing impacts and risks, potentially increasing vulnerability to those risks. The resulting decision-making guidance on impacts and adaptation follows a rational-linear process that identifies potential risks and then evaluates management responses (e.g., Carter et al., 1994; Feenstra et al., 1998; Parry and Carter, 1998; Fisher et al., 2007). This process has been challenged on the grounds that it does not adequately address the diverse contexts within which climate decisions are being made, often neglects existing decision-making processes, and overlooks many cultural and behavioral aspects of decision making (Smit and Wandel, 2006; Sarewitz and Pielke, 2007; Dovers, 2009; Beck, 2010). While more recent guidance on CIAV decision making typically accounts for sectoral, regional, and socioeconomic characteristics (Section 21.3), the broader decision-making literature is still not fully reflected in current methods. This is despite an increasing emphasis on the roles of societal impacts and responses to climate change in decision-making methodologies (*high confidence*) (Sections 1.1, 1.2, 21.2.1).

The main considerations that inform the decision-making contexts addressed here are knowledge generation and exchange, who makes and implements decisions, and the issues being addressed and how these can be addressed. These decisions occur within a broader social and cultural environment. Knowledge generation and exchange includes knowledge generation, development, brokering, exchange, and application to practice. Decision makers include policymakers, managers, planners, and practitioners, and range from individuals to organizations and institutions (Table 21-1). Relevant issues include all areas affected directly and indirectly by climate impacts or by responses to those impacts, covering diverse aspects of society and the environment. These issues include consideration of values, purpose, goals, available resources, the time over which actions are expected to remain effective, and the extent to which the objectives being pursued are regarded as appropriate. The purpose of the decision in question, for example, assessment, strategic planning, or implementation, will also define the framework and tools needed to enable the process. This chapter neither provides any standard template or instructions for decision making, nor does it endorse particular decisions over others.

The remainder of this chapter is organized as follows. Section 2.1.2 addresses risk management, which provides an overall framework suitable for CIAV decision making; Section 2.1.3 introduces decision support; Section 2.2 discusses contexts for decision making; Section 2.3 discusses methods, tools, and processes; Section 2.4 discusses support for and application of decision making; and Section 2.5 describes some of the broader contexts influencing CIAV decision making.

2.1.1. Decision-Making Approaches in this Report

The overarching theme of the chapter and the AR5 report is managing current and future climate risks (Sections 1.2.4, 16.2, 19.1), principally through adaptation (Chapters 14 to 17), but also through resilience and sustainable development informed by an understanding of both impacts and vulnerability (Section 19.2). The International Standard ISO:31000 defines risk as *the effect of uncertainty on objectives* (ISO, 2009) and the Working Group II AR5 Glossary defines risk as *The potential for consequences where something of human value (including humans themselves) is at stake and where the outcome is uncertain* (Rosa, 2003). However, the Glossary also refers to a more operational definition for assessing climate-related hazards: *risk is often represented as probability of occurrence of hazardous events or trends multiplied by the consequences if these events occur.* Risk can also refer to an uncertain opportunity or benefit (see Section 2.2.1.3). This chapter takes a broader perspective than the latter by including risks associated with taking action (e.g., will this adaptation strategy be successful?) and the broader socially constructed risks that surround "climate change" (e.g., fatalism, hope, opportunity, and despair).

Because all decisions on CIAV are affected by uncertainty and focus on valued objectives, all can be considered as decisions involving risk (e.g., Giddens, 2009) (*high confidence*). AR4 endorsed iterative risk management as a suitable decision support framework for CIAV assessment because it offers formalized methods for addressing uncertainty, involving stakeholder participation, identifying potential policy responses, and evaluating those responses (Carter et al., 2007; IPCC, 2007b; Yohe et al., 2007). The literature shows significant advances on all these topics since AR4 (Section 1.1.4), greatly expanding methodologies for assessing impacts, adaptation, and vulnerability in a risk context (Agrawala and Fankhauser, 2008; Hinkel, 2011; Jones and Preston, 2011; Preston et al., 2011).

Many different risk methodologies, such as financial, natural disaster, infrastructure, environmental health, and human health, are relevant for CIAV decision making (*very high confidence*). Each methodology utilizes a variety of different tools and methods. For example, the standard CIAV methodology follows a top-down cause and effect pathway as outlined previously. Others follow a bottom-up pathway, starting with a set of decision-making goals that may be unrelated to climate and consider how climate may affect those goals (see also Sections 15.2.1, 15.3.1). Some methodologies such as vulnerability, resilience, and livelihood assessments are often considered as being different from traditional risk assessment, but may be seen as dealing with particular stages within a longer term iterative risk management process. For example, developing resilience can be seen as managing a range of potential risks that are largely unpredictable; and sustainable development aims to develop a social-ecological system robust to climate risks.

A major aim of decision making is to make good or better decisions. Good and better decisions with respect to climate adaptation are frequently mentioned in the literature but no universal criterion exists for a good decision, including a good climate-related decision (Moser and Ekstrom, 2010). This is reflected in the numerous framings linked to adaptation decision making, each having its advantages and disadvantages

Frequently Asked Questions

FAQ 2.1 | What constitutes a good (climate) decision?

No universal criterion exists for a good decision, including a good climate-related decision. Seemingly reasonable decisions can turn out badly, and seemingly unreasonable decisions can turn out well. However, findings from decision theory, risk governance, ethical reasoning, and related fields offer general principles that can help improve the quality of decisions made.

Good decisions tend to emerge from processes in which people are explicit about their goals; consider a range of alternative options for pursuing their goals; use the best available science to understand the potential consequences of their actions; carefully consider the trade-offs; contemplate the decision from a wide range of views and vantages, including those who are not represented but may be affected; and follow agreed-upon rules and norms that enhance the legitimacy of the process for all those concerned. A good decision will be implementable within constraints such as current systems and processes, resources, knowledge, and institutional frameworks. It will have a given lifetime over which it is expected to be effective, and a process to track its effectiveness. It will have defined and measurable criteria for success, in that monitoring and review is able to judge whether measures of success are being met, or whether those measures, or the decision itself, need to be revisited.

A good climate decision requires information on climate, its impacts, potential risks, and vulnerability to be integrated into an existing or proposed decision-making context. This may require a dialog between users and specialists to jointly ascertain how a specific task can best be undertaken within a given context with the current state of scientific knowledge. This dialog may be facilitated by individuals, often known as knowledge brokers or extension agents, and boundary organizations, who bridge the gap between research and practice. Climate services are boundary organizations that provide and facilitate knowledge about climate, climate change, and climate impacts for planning, decision making, and general societal understanding of the climate system.

(Preston et al., 2013; see also Section 15.2.1). Extensive evidence from the decision sciences shows that good scientific and technical information alone is rarely sufficient to result in better decisions (Bell and Lederman, 2003; Jasanoff, 2010; Pidgeon and Fischhoff, 2011) (*high confidence*). Aspects of decision making that distinguish climate change from most other contexts are the long time scales involved, the pervasive impacts and resulting risks, and the "deep" uncertainties attached to many of those risks (Kandlikar et al., 2005; Ogden and Innes, 2009; Lempert and McKay, 2011). These uncertainties include not only future climate but also socioeconomic change and potential changes in norms and values within and across generations.

2.1.2. Iterative Risk Management

Iterative risk management involves an ongoing process of assessment, action, reassessment, and response (Kambhu et al., 2007; IRGC, 2010) that will continue—in the case of many climate-related decisions—for decades if not longer (National Research Council, 2011). This development is consistent with an increasing focus on risk governance (Power, 2007; Renn, 2008), the integration of climate risks with other areas of risk management (Hellmuth et al., 2011; Measham et al., 2011), and a wide range of approaches for structured decision making involving process uncertainty (Ohlson et al., 2005; Wilson and McDaniels, 2007; Ogden and Innes, 2009; Martin et al., 2011).

Two levels of interaction can be recognized within the iterative risk management process: one internal and one external (Figure 2-1). External factors are present through the entire process and shape the process outcomes. The internal aspects describe the adaptation process itself. The first major internal iteration (in yellow) reflects the interplay with the analysis phase by addressing the interactions between evolving risks and their feedbacks (not shown) and during the development and choice of options. This process may also require a revision of criteria and objectives. This phase ends with decisions on the favored options being made. A further internal iteration covers the implementation of actions and their monitoring and review (in orange). Throughout all stages the process is reflexive, in order to enable changes in knowledge, risks, or circumstances to be identified and responded to. At the end of the implementation stage, all stages are evaluated and the process starts again with the scoping phase. Iterations can be successive, on a set timetable, triggered by specific criteria or informally by new information informing risk or a change in the policy environment. An important aspect of this process is to recognize emergent risks and respond to them (Sections 19.2.3, 19.2.4, 19.2.5, 19.3).

Complexity is an important attribute for framing and implementing decision-making processes (*very high confidence*). Simple, well-bounded contexts involving cause and effect can be addressed by straightforward linear methods. Complicated contexts require greater attention to process but can generally be unravelled, providing an ultimate solution (Figure 2-2). However, when complex environments interact with conflicting values they become associated with wicked problems. Wicked problems are not well bounded, are framed differently by various groups and individuals, harbor large scientific to existential uncertainties and have unclear solutions and pathways to those solutions (Rittel and Webber,

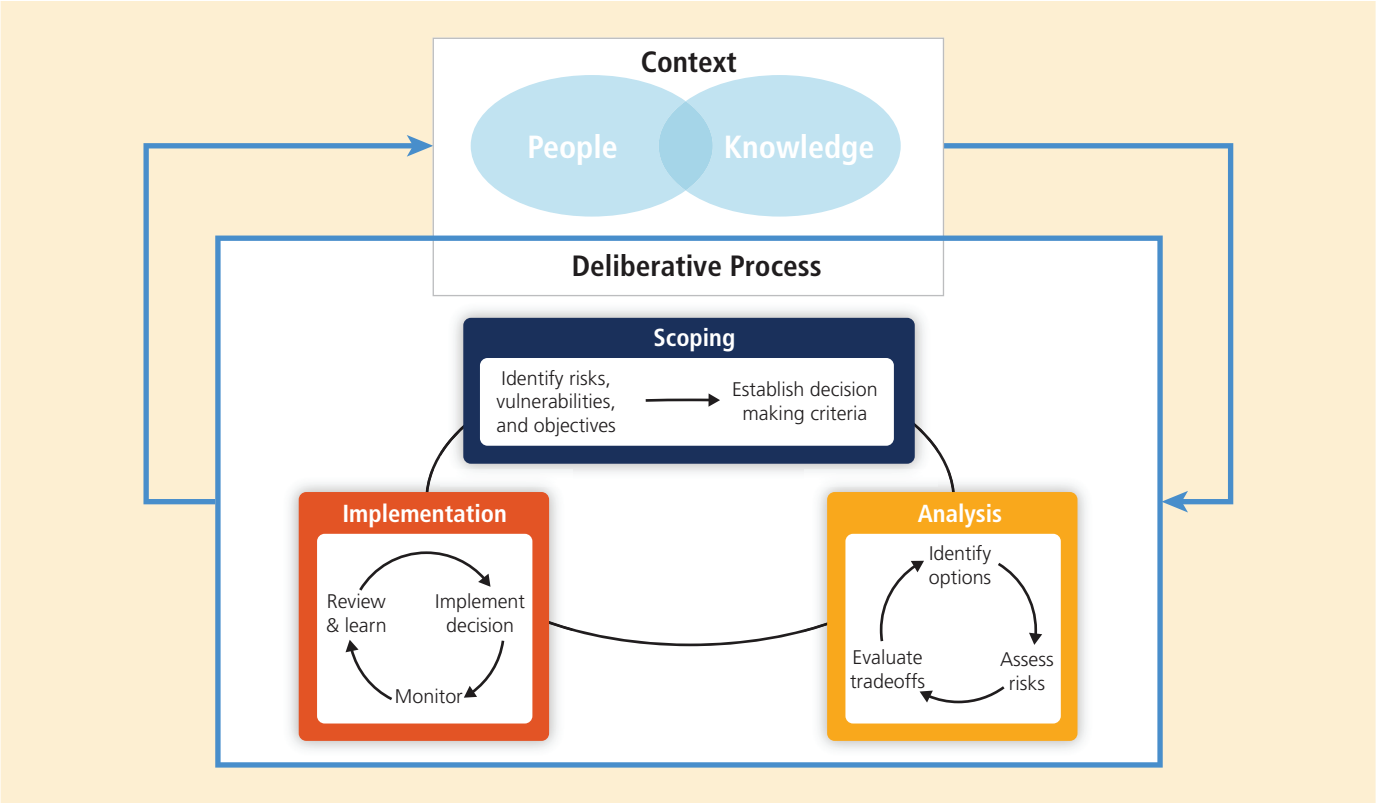


Figure 2-1 | Iterative risk management framework depicting the assessment process, and indicating multiple feedbacks within the system and extending to the overall context (adapted from Willows and Connell, 2003).

1973; Australian Public Service Commission, 2007). Such "deep uncertainty" cannot easily be quantified (Dupuy and Grinbaum, 2005; Kandlikar et al., 2005). Another important attribute of complex systems is *reflexivity*, where cause and effect feed back into each other (see Glossary). For example, actions taken to manage a risk will affect the outcomes, requiring iterative processes of decision making (*very high confidence*). Under climate change, calculated risks will also change with time as new knowledge becomes available (Ranger et al., 2010).

In complex situations, sociocultural and cognitive-behavioral contexts become central to decision making. This requires combining the scientific understanding of risk with how risks are framed and perceived by individuals, organizations, and institutions (Hansson, 2010). For that reason, formal risk assessment is moving from a largely technocratic exercise carried out by experts to a more participatory process of decision support (Fiorino, 1990; Pereira and Quintana, 2002; Renn, 2008), although this process is proceeding slowly (Christoplos et al., 2001; Pereira and Quintana, 2002; Bradbury, 2006; Mercer et al., 2008).

Different traditional and modern epistemologies, or "ways of knowing" exist for risk (Hansson, 2004; Althaus, 2005; Hansson, 2010), vulnerability (Weichselgartner, 2001; O'Brien et al., 2007), and adaptation assessments (Adger et al., 2009), affecting the way they are framed by various disciplines and are also understood by the public (Garvin, 2001; Adger, 2006; Burch and Robinson, 2007). These differences have been identified as a source of widespread misunderstanding and disagreement. They are also used to warn against a uniform epistemic approach (Hulme, 2009; Beck, 2010), a critique that has been leveled against previous IPCC assessments (e.g., Hulme and Mahony, 2010).

The following three types of risk have been identified as important epistemological constructs (Thompson, 1986; Althaus, 2005; Jones, 2012):

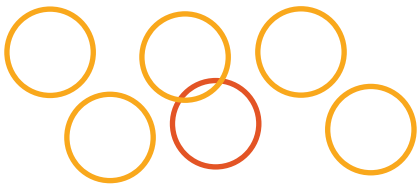
1. Idealized risk: the conceptual framing of the problem at hand. For example, dangerous anthropogenic interference with the climate system is how climate change risk is idealized within the UNFCCC.
2. Calculated risk: the product of a model based on a mixture of historical (observed) and theoretical information. Frequentist or recurrent risks often utilize historical information whereas single-event risks may be unprecedented, requiring a more theoretical approach.
3. Perceived risk: the subjective judgment people make about an idealized risk (see also Section 19.6.1.4).

These different types show risk to be partly an objective threat of harm and partly a product of social and cultural experience (Kasperson et al., 1988; Kasperson, 1992; Rosa, 2008). The aim of calculating risk is to be as objective as possible, but the subjective nature of idealized and perceived risk reflects the division between positivist (imposed norms) and constructivist (derived norms) approaches to risk from the natural and social sciences respectively (Demeritt, 2001; Hansson, 2010). Idealized risk is important for framing and conceptualizing risk and will often have formal and informal status in the assessment process, contributing to both calculated and perceived risk. These types of risk combine at the societal scale as socially constructed risk, described and









Characteristics of decision making	Simple risk	Complicated risk	Complex risk
Methodology	Linear, cause and effect	Top down and/or bottom up, iterative	Iterative and/or adaptive, ongoing and systemic
Approach	Analytic and technical	Collaborative process with technical input	Process driven. Frame and model multiple drivers and valued outcomes
Stakeholder strategy	Communication	Collaboration	Deliberation, creating shared understanding and ownership
Mental models	Common model	Negotiated and shared	Contested initially and negotiated over project
Values and outcomes	Widely accepted	Negotiated over project by user perspectives and calculated risk	Contested initially and negotiated over project
Monitoring	Straightforward	With review and trigger points	As real-time as possible, adaptive with management feedback and trigger points

Figure 2-2 | Hierarchy of simple, complicated, and complex risks, showing how perceived risks multiply and become less connected with calculated risk with increasing complexity. Also shown are major characteristics of assessment methods for each level of complexity.

assessed in a wide range of research literature such as psychology, anthropology, geography, ethics, sociology, and political science (see Sections 2.2.1.2, 19.6.1.4).

Acceptance of the science behind controversial risks is strongly influenced by social and cultural values and beliefs (Leiserowitz, 2006; Kahan et al., 2007; Brewer and Pease, 2008). Risk perceptions can be amplified socially where events pertaining to hazards interact with psychological, social, institutional, and cultural processes in ways that heighten or attenuate individual and social perceptions of risk and shape risk behavior (Kasperson et al., 1988; Renn et al., 1992; Pidgeon et al., 2003; Rosa, 2003; Renn, 2011). The media have an important role in propagating both calculated and perceived risk (Llasat et al., 2009), sometimes to detrimental effect (Boykoff and Boykoff, 2007; Oreskes and Conway, 2010; Woods et al., 2012).

Understanding how these perceptions resonate at an individual and collective level can help overcome constraints to action (Renn, 2011). Science is most suited to calculating risk in areas where it has predictive skill and will provide better estimates than may be obtained through more informal methods (Beck, 2000), but an assessment of what is at risk generally needs to be accepted by stakeholders (Eiser et al., 2012). Therefore, the science always sits within a broader social setting (Jasanoff, 1996; Demeritt, 2001; Wynne, 2002; Demeritt, 2006), often requiring a systems approach where science and policy are investigated in tandem, rather than separately (Pahl-Wostl, 2007; Ison, 2010) (*very high confidence*). These different types of risk give rise to complex interactions between formal and informal knowledge that cannot be bridged by better science or better predictions but require socially and culturally mediated processes of engagement (*high confidence*).

2.1.3. Decision Support

The concept of *decision support* provides a useful framework for understanding how risk-based concepts and information can help enhance decision making (McNie, 2007; National Research Council Panel on Design Issues for the NOAA Sectoral Applications Research Program et al., 2007; Moser, 2009; Romsdahl and Pyke, 2009; Kandlikar et al., 2011; Pidgeon and Fischhoff, 2011) The concept also helps situate methods, tools, and processes intended to improve decision making within appropriate institutional and cultural contexts.

Decision support is defined as "a set of processes intended to create the conditions for the production of decision-relevant information and for its appropriate use" (National Research Council, 2009a, p. 33). Information is decision-relevant if it yields deeper understanding of, or is incorporated into making a choice that improves outcomes for decision makers and stakeholder or precipitates action to manage known risks. Effective decision support provides users with information they find useful because they consider it credible, legitimate, actionable, and salient (e.g., Jones et al., 1999; Cash et al., 2003; Mitchell, 2006; Reid et al., 2007). Such criteria can be used to evaluate decision support and such evaluations lead to common principles of effective decision support, which have been summarized in National Research Council (2009b) as:

- Begins with user's needs, not scientific research priorities. Users may not always know their needs in advance, so user needs are often developed collaboratively and iteratively among users and researchers.
- Emphasizes processes over products. Though the information products are important, they are likely to be ineffective if they are not developed to support well-considered processes.

- Incorporates systems that link users and producers of information. These systems generally respect the differing cultures of decision makers and scientists, but provide processes and institutions that effectively link individuals from these differing communities.
- Builds connections across disciplines and organizations, in order to provide for the multidisciplinary character of the needed information and the differing communities and organizations in which this information resides.
- Seeks institutional stability, either through stable institutions and/or networks, which facilitates building the trust and familiarity needed for effective links and connections among information users and producers in many different organizations and communities.
- Incorporates learning, so that all parties recognize the need for and contribute to the implementation of decision support activities structured for flexibility, adaptability, and learning from experience.

These principles can lead to different decision support processes depending on the stage and context of the decision in question. For instance, decision support for a large water management agency operating an integrated system serving millions of people will have different needs than a small town seeking to manage its groundwater supplies. A community in the early stages of developing a response to climate change may be more focused on raising awareness of the issue among its constituents, while a community with a well-developed understanding of its risks may be more focused on assessing trade-offs and allocating resources.

2.2. Contexts for Decision Making

This section surveys aspects of decision making that relate to context setting. Social context addresses cultural values, psychology, language, and ethics (Section 2.2.1) and institutional context covers institutions and governance (Section 2.2.2).

2.2.1. Social Context

Decision support for CIAV must recognize that diverse values, language uses, ethics, and human psychological dimensions play a crucial role in the way that people use and process information and take decisions (Kahan and Braman, 2006; Leiserowitz, 2006). As illustrated in Figure 2-1, the context defines and frames the space in which decision-making processes operate.

2.2.1.1. Cultural Values and Determinants

Cultural differences allocate values and guide socially mediated change. Five value dimensions that show significant cross-national variations are: power distance, individualism/collectivism, uncertainty avoidance, long-/short-term orientation, and masculinity/femininity (Hofstede, 1980, 2001; Hofstede et al., 2010). Power distance and individualism/collectivism both show a link to climate via latitude; the former relates to willingness to conform to top-down directives, whereas the latter relates to the potential efficacy of market-/community-based strategies. Uncertainty avoidance and long-term orientation show considerable variation between countries (Hofstede et al., 2010), potentially producing significant differences in risk perception and agency.

Environmental values have also been linked to cultural orientation. Schultz et al. (2004) identified the association between self and nature in people as being implicit—informing actions without specific awareness. A strong association was linked to a more connected self and a weaker association with a more egoistic self. Explicit environmental values can substantially influence climate change-related decision-making processes (Nilsson et al., 2004; Milfont and Gouveia, 2006; Soyez et al., 2009) and public behavior toward policies (Stern and Dietz, 1994; Xiao and Dunlap, 2007). Schaffrin (2011) concludes that geographical aspects, vulnerability, and potential policy benefits associated with a given issue can influence individual perceptions and willingness to act (De Groot and Steg, 2007, 2008; Shwom et al., 2008; Milfont et al., 2010). Cultural values can interrelate with specific physical situations of climate change (Corraliza and Berenguer, 2000), or seasonal and meteorological factors influencing people's implicit connections with nature (Duffy and Verges, 2010). Religious and sacred values are also important (Goloubinoff, 1997; Katz et al., 2002; Lammel et al., 2008), informing the perception of climate change and risk, as well as the actions to adapt (Crate and Nuttal, 2009; see also Section 16.3.1.3). The role of protected values (values that people will not trade off, or negotiate) can also be culturally and spiritually significant (Baron and Spranca, 1997; Baron et al., 2009; Hagerman et al., 2010). Adger et al. (2013) emphasize the importance of cultural values in assessing risks and adaptation options, suggesting they are at least as important as economic values in many cases, if not more so. These aspects are important for framing and conceptualizing CIAV decision making. Cultural and social barriers are described in Section 16.3.2.7.

Two distinct ways of thinking—holistic and analytical thinking—reflect the relationship between humans and nature and are cross-culturally and even intra-culturally diverse (Gagnon Thompson and Barton, 1994; Huber and Pedersen, 1997; Atran et al., 2005; Ignatow, 2006; Descola, 2010; Ingold, 2011). Holistic thinking is primarily gained through experience and is dialectical, accepting contradictions and integrating multiple perspectives. Characteristic of collectivist societies, the holistic conceptual model considers that social obligations are reciprocal and individuals take an active part in the community for the benefit of all (Peng and Nisbett, 1999; Nisbett et al., 2001; Lammel and Kozakai, 2005; Nisbett and Miyamoto, 2005). Analytical thinking isolates the object from its broader context, understanding its characteristics through categorization, and predicting events based on intrinsic rules. In the analytic conceptual model, individual interests take precedence over the collective; the self is independent and communication comes from separate fields. These differences influence the understanding of complex systemic phenomena such as climate change (Lammel et al., 2011, 2012, 2013) and decision-making practices (Badke-Schaub and Strohschneider, 1998; Strohschneider and Güss, 1999; Güss et al., 2010).

The above models vary greatly across the cultural landscape, but neither model alone is sufficient for decision making in complex situations (*high confidence*). At a very basic level, egalitarian societies may respond more to community based adaptation in contrast to more individualistic societies that respond to market-based forces (*medium confidence*). In small-scale societies, knowledge about climate risks are often integrated

into a holistic view of community and environment (e.g., Katz et al., 2002; Strauss and Orlove, 2003; Lammel et al., 2008). Many studies highlight the importance of integrating local, traditional knowledge with scientific knowledge when assessing CIAV (Magistro and Roncoli, 2001; Krupnik and Jolly, 2002; Vedwan, 2006; Nyong et al., 2007; Dube and Sekhwela, 2008; Crate and Nuttal, 2009; Mercer et al., 2009; Roncoli et al., 2009; Green and Raygorodetsky, 2010; Orlove et al., 2010; Crate, 2011; Nakashima et al., 2012; see also Sections 12.3, 12.3.1, 12.3.2, 12.3.3, 12.3.4, 14.4.5, 14.4.7, 15.3.2.7, 25.8.2, 28.2.6.1, 28.4.1). For example, a case study in Labrador (Canada) demonstrated the need to account for local material and symbolic values because they shape the relationship to the land, underlie the way of life, influence the intangible effects of climate change, and can lead to diverging views on adaptations (Wolf et al., 2012). In Kiribati, the integration of local cultural values attached to resources/assets is fundamental to adaptation planning and water management; otherwise technology will not be properly utilized (Kuruppu, 2009).

2.2.1.2. Psychology

Psychology plays a significant role in climate change decision making (Gifford, 2008; Swim et al., 2010; Anderson, 2011). Important psychological factors for decision making include perception, representation, knowledge acquisition, memory, behavior, emotions, and understanding of risk (Böhm and Pfister, 2000; Leiserowitz, 2006; Lorenzoni et al., 2006; Oskamp and Schultz, 2006; Sterman and Sweeney, 2007; Gifford, 2008; Kazdin, 2009; Sundblad et al., 2009; Reser et al., 2011; Swim et al., 2011).

Psychological research contributes to understanding on both risk perception and the process of adaptation. Several theories, such as multi-attribute utility theory (Keeney, 1992), prospect theory (Kahneman and Tversky, 1979; Hardman, 2009), and cumulative prospect theory relate to decision making under uncertainty (Tversky and Kahneman, 1992), especially to risk perception and agency. Adaptation in complex situations pits an unsure gain against an unsure loss, so creates an asymmetry in preference that magnifies with time as gains/losses are expected to accrue in future. Decisions focusing on values and uncertainty are therefore subject to framing effects. Recent cognitive approaches include the one-reason decision process that uses limited data in a limited time period (Gigerenzer and Goldstein, 1996) or decision by sampling theory that samples real-world data to account for the cognitive biases observed in behavioral economics (Stewart et al., 2006; Stewart and Simpson, 2008). Risk perception is further discussed in Section 19.6.1.4.

Responses to new information can modify previous decisions, even producing contradictory results (Grothmann and Patt, 2005; Marx et al., 2007). Although knowledge about climate change is necessary (Milfont, 2012), understanding such knowledge can be difficult (Rajeev Gowda et al., 1997; Boyes et al., 1999; Andersson and Wallin, 2000). Cognitive obstacles in processing climate change information include psychological distances with four theorized dimensions: temporal, geographical, social distance, and uncertainty (Spence et al., 2012; see also Section 25.4.3). Emotional factors also play an important role in climate change perception, attitudes, decision making, and actions (Meijnders et al., 2002; Leiserowitz, 2006; Klöckner and Blöbaum, 2010; Fischer and Glenk 2011; Roeser, 2012) and even shape organizational decision making (Wright and Nyberg, 2012). Other studies on attitudes and behaviors relevant to climate change decision making, include place attachment (Scannell and Gifford, 2013; see also Section 25.4.3), political affiliation (Davidson and Haan, 2011), and perceived costs and benefits (Tobler et al., 2012). Time is a critical component of action-based decision making (Steel and König, 2006). As the benefits of many climate change actions span multiple temporal scales, this can create a barrier to effective motivation for decisions through a perceived lack of value associated with long-term outcomes.

Protection Motivation Theory (Rogers, 1975; Maddux and Rogers, 1983), which proposes that a higher personal perceived risk will lead to a higher motivation to adapt, can be applied to climate change-related problems (e.g., Grothmann and Reusswig, 2006; Cismaru et al., 2011). The person-relative-to-event approach predicts human coping strategies as a function of the magnitude of environmental threat (Mulilis and Duval, 1995; Duval and Mulilis, 1999; Grothmann et al., 2013). People's responses to environmental hazards and disasters are represented in the multistage Protective Action Decision Model (Lindell and Perry, 2012). This model helps decision makers to respond to long-term threat and apply it in long-term risk management. Grothmann and Patt (2005) developed and tested a socio-cognitive model of proactive private adaptation to climate change showing that perceptions of adaptive capacities were important as well as perceptions of risk. If a perceived high risk is combined with a perceived low adaptive capacity (see Section 2.4.2.2; Glossary), the response is fatalism, denial, and wishful thinking.

Best-practice methods for incorporating and communicating information about risk and uncertainties into decisions about climate change (Climate Change Science Program, 2009; Pidgeon and Fischhoff, 2011) suggests that effective communication of uncertainty requires products and processes that (1) closes psychological distance, explaining why this information is important to the recipient; (2) distinguishes between and explains different types of uncertainty; (3) establishes self-agency, explaining what the recipient can do with the information and ways to make decisions under uncertainty (e.g., precautionary principle, iterative risk-management); (4) recognizes that each person's view of risks and opportunities depends on their values; (5) recognizes that emotion is a critical part of judgment; and (6) provides mental models that help recipients to understand the connection between cause and effect. Information providers also need to test their messages, as they may not be communicating what they think they are.

2.2.1.3. Language and Meaning

Aspects of decision making concerned with language and meaning include framing, communication, learning, knowledge exchange, dialog, and discussion. Most IPCC-related literature on language and communication deals with definitions, predictability, and incomplete knowledge, with less emphasis given to other aspects of decision support such as learning, ambiguity, contestedness, and complexity. Three important areas assessed here are definitions, risk language and communication, and narratives.

Decision-making processes need to accommodate both specialist and non-specialist meanings of the concepts they apply. Various disciplines often have different definitions for the same terms or use different terms for the same action or object, which is a major barrier for communication and decision making (Adger, 2003; see also Chapter 21). For example, adaptation is defined differently with respect to biological evolution, climate change, and social adaptation. Budescu et al. (2012) found that people prefer imprecise wording but precise numbers when appropriate. Personal lexicons vary widely, leading to differing interpretations of uncertainty terms (Morgan et al., 1990); in the IPCC's case leading to uncertainty ranges often being interpreted differently than intended (Patt and Schrag, 2003; Patt and Dessai, 2005; Budescu et al., 2012). Addressing both technical and everyday meanings of key terms can help bridge the analytic and emotive aspects of cognition. For example, words like danger, disaster, uncertainty, and catastrophe have technical and emotive aspects (Britton, 1986; Carvalho and Burgess, 2005). Terms where this issue is especially pertinent include adaptation, vulnerability, risk, dangerous, catastrophe, resilience, and disaster. Other words have definitional issues because they contain different epistemological frames; sustainability and risk are key examples (Harding, 2006; Hamilton et al., 2007). Many authors advocate that narrow definitions focused solely on climate need to be expanded to suit the context in which they are being used (Huq and Reid, 2004; O'Brien et al., 2007; Schipper, 2007). This is a key role for risk communication, ensuring that different types of knowledge are integrated within decision context and outlining the different values—implicit and explicit—involved in the decision process (e.g., Morgan, 2002; Lundgren and McMakin, 2013).

The language of risk has a crucial role in framing and belief. Section 2.1.2 described over-arching and climate-specific definitions but risk enters into almost every aspect of social discourse, so is relevant to how risk is framed and communicated (e.g., Hansson, 2004). Meanings of risk range from its ordinary use in everyday language to power and political discourse, health, emergency, disaster, and seeking benefits, ranging from specific local meanings to broad-ranging concepts such as the risk society (Beck and Ritter, 1992; Beck, 2000; Giddens, 2000). Complex framings in the word risk (Fillmore and Atkins, 1992; Hamilton et al., 2007) feature in general English as both a noun and a verb, reflecting harm and chance with negative and positive senses (Fillmore and Atkins, 1992). Problem analysis applies risk as a noun (at-risk), whereas risk management applies risk as a verb (to-risk) (Jones, 2011). For simple risks, this transition is straightforward because of agreement around values and agency (Figure 2-2). In complex situations, risk as a problem and as an opportunity can compete with each other, and if socially amplified can lead to action paralysis (Renn, 2011). For example, unfamiliar adaptation options that seem to be risky themselves will force a comparison between the risk of maladaptation and future climate risks, echoing the risk trap where problems and solutions come into conflict (Beck, 2000). Fear-based dialogs in certain circumstances can cause disengagement (O'Neill and Nicholson-Cole, 2009), by emphasizing risk aversion. Young (2013) proposes framing adaptation as a solution to overcome the limitations of framing through the problem, and links it to innovation, which provides established pathways for the implementation of actions, proposing a problem-solution framework linking decision making to action. Framing decisions and modeling actions on positive risk-seeking behavior can help people to address uncertainty as opportunity (e.g., Keeney, 1992).

Narratives are accounts of events with temporal or causal coherence that may be goal directed (László and Ehmann, 2012) and play a key role in communication, learning, and understanding. They operate at the personal to societal scales, are key determinants of framing, and have a strong role in creating social legitimacy. Narratives can also be non-verbal: visualization, kinetic learning by doing, and other sensory applications can be used to communicate science and art and to enable learning through play (Perlovsky, 2009; Radford, 2009). Narratives of climate change have evolved over time and invariably represent uncertainty and risk (Hamblyn, 2009) being characterized as tools for analysis, communication, and engagement (Cohen, 2011; Jones et al., 2013; Westerhoff and Robinson, 2013) by:

- Providing a social and environmental context to modelled futures (Arnell et al., 2004; Kriegler et al., 2012; O'Neill et al., 2014), by describing aspects of change that drive or shape those futures as part of scenario construction (Cork et al., 2012).
- Communicating knowledge and ideas to increase understanding and increase agency framing it in ways so that actions can be implemented (Juhola et al., 2011) or provide a broader socio-ecological context to specific knowledge (Burley et al., 2012). These narratives bridge the route between scientific knowledge and local understandings of adaptation, often by working with multiple actors in order to creatively explore and develop collaborative potential solutions (Turner and Clifton, 2009; Paton and Fairbairn-Dunlop, 2010; Tschakert and Dietrich, 2010).
- Exploring responses at an individual/institutional level to an aspect of adaptation, and communicating that experience with others (Bravo, 2009; Cohen, 2011). For example, a community that believes itself to be resilient and self-reliant is more likely to respond proactively, contrasted to a community that believes itself to be vulnerable (Farbotko and Lazrus, 2012). Bravo (2009) maintains that narratives of catastrophic risk and vulnerability demotivate indigenous peoples whereas narratives combining scientific knowledge and active citizenship promote resilience (Section2.5.2).

2.2.1.4. Ethics

Climate ethics can be used to formalize objectives, values (Section 2.2.1.1), rights, and needs into decisions, decision-making processes, and actions (see also Section 16.7). Principal ethical concerns include intergenerational equity; distributional issues; the role of uncertainty in allocating fairness or equity; economic and policy decisions; international justice and law; voluntary and involuntary levels of risk; cross-cultural relations; and human relationships with nature, technology, and the sociocultural world. Climate change ethics have been developing over the last 20 years (Jamieson, 1992, 1996; Gardiner, 2004; Gardiner et al., 2010), resulting in a substantial literature (Garvey, 2008; Harris, 2010; O'Brien et al., 2010; Arnold, 2011; Brown, 2012; Thompson and Bendik-Keymer, 2012). Equity, inequity, and responsibility are fundamental concepts in the UNFCCC (UN, 1992) and therefore are important considerations in policy development for CIAV. Climate ethics examine effective responsible and "moral" decision making and action, not only by governments but also by individuals (Garvey, 2008).

An important discourse on equity is that industrialized countries have, through their historical emissions, created a natural debt (Green and

Smith, 2002). Developing nations experience this debt through higher impacts and greater vulnerability combined with limited adaptive capacity. Regional inequity is also of concern (Green and Smith, 2002), particularly indigenous or marginalized populations exposed to current climate extremes, who may become more vulnerable under a changing climate (Tsosie, 2007; see also Section 12.3.3). With respect to adaptation assessment, cost-benefit or cost-effectiveness methods combined with transfer of funds will not satisfy equity considerations (Broome, 2008; see also Section 17.3.1.4) and modifications such as equity-weighting (Kuik et al., 2008) and cost-benefit under uncertainty (Section 17.3.2.1), have not been widely used. Adaptation measures need to be evaluated by considering their equity implications (Section 17.3.1.4) especially under uncertainty (Hansson, 2004).

Intergenerational issues are frequently treated as an economic problem, with efforts to address them through an ethical framework proving to be controversial (Nordhaus, 2007; Stern and Treasury of Great Britain, 2007; Stern, 2008). However, future harm may make the lives of future generations difficult or impossible, dilemmas that involve ethical choices (Broome, 2008), therefore discount rates matter (Section 17.4.4.4). Some authors question whether the rights and interests of future people should even be subject to a positive discount rate (Caney, 2009). Future generations can neither defend themselves within current economic frameworks (Gardiner, 2011) nor can these frameworks properly account for the dangers, interdependency, and uncertainty under climate change (Nelson, 2011), even though people's values may change over time (Section 16.7). The limits to adaptation raise questions of irreversible loss and the loss of unique cultural values that cannot necessarily be easily transferred (Section 16.7), contributing to key vulnerabilities and informing ethical issues facing mitigation (see Section 19.7.1).

Environmental ethics considers the decisions humans may make concerning a range of biotic impacts (Schalow, 2000; Minteer and Collins, 2010; Nanda, 2012; Thompson and Bendik-Keymer, 2012). Intervention in natural systems through "assisted colonization" or "managed relocation" raises important ethical and policy questions (Minteer and Collins, 2010; Section 4.4.2.4) that include the risk of unintended consequences (Section 4.4.4). Various claims are made for a more pragmatic ethics of ecological decision making (Minteer and Collins, 2010), consideration of moral duties toward species (Sandler, 2009), and ethically explicit and defendable decision making (Minteer and Collins, 2005a,b).

Cosmopolitan ethics and global justice can lead to successful adaptation and sustainability (Caney, 2006; Harris, 2010) and support collective decision making on public matters through voting procedures (Held, 2004). Ethics also concerns the conduct and application of research, especially research involving stakeholders. Action-based and participatory research requires that a range of ethical guidelines be followed, taking consideration of the rights of stakeholders, respect for cultural and practical knowledge, confidentiality, dissemination of results, and development of intellectual property (Macaulay et al., 1999; Kindon et al., 2007; Daniell et al., 2009; Pearce et al., 2009). Ethical agreements and processes are an essential part of participatory research, whether taking part as behavioral change processes promoting adaptation or projects of collaborative discovery (*high confidence*). Although the climate change ethics literature is rapidly developing, the related practice of decision making and implementation needs further development. Ethical and equity issues are discussed in WGIII AR5 Chapter 3.

2.2.2. Institutional Context

2.2.2.1. Institutions

Institutions are rules and norms held in common by social actors that guide, constrain, and shape human interaction (North, 1990; Glossary). Institutions can be formal, such as laws and policies, or informal, such as norms and conventions. Organizations—such as parliaments, regulatory agencies, private firms, and community bodies—develop and act in response to institutional frameworks and the incentives they frame (Young et al., 2008). Institutions can guide, constrain, and shape human interaction through direct control, through incentives, and through processes of socialization (Glossary). Virtually all CIAV decisions will be made by or influenced by institutions because they shape the choices made by both individuals and organizations (Bedsworth and Hanak, 2012). Institutional linkages are important for adaptation in complex and multi-layered social and biophysical systems such as coastal areas (Section 5.5.3.2) and urban systems (Section 8.4.3.4), and are vital in managing health (Section 11.6), human security (Sections 12.5.1, 12.6.2), and poverty (Section 13.1). Institutional development and interconnectedness are vital in mediating vulnerability in social-ecological systems to changing climate risks, especially extremes (Chapters 5, 7 to 9, 11 to 13).

The role of institutions as actors in adaptation are discussed in Section 14.4, in planning and implementing adaptation in Section 15.5, and in providing barriers and opportunities in Section 16.3. Their roles can be very diverse. Local institutions usually play important roles in accessing resources and in structuring individual and collective responses (Agarwal, 2010; see also Section 14.4.2) but Madzwamuse (2010) found that in Africa, state-level actors had significantly more influence on formal adaptation policies than did civil society and local communities. This suggests a need for greater integration and cooperation among institutions of all levels (Section 15.5.1.2). Section 14.2.3 identifies four institutional design issues: flexibility; potential for integration into existing policy plans and programs; communication, coordination, and cooperation; and the ability to engage with multiple stakeholders.

Institutions are instrumental in facilitating adaptive capacity, by utilizing characteristics such as variety, learning capacity, room for autonomous change, leadership, availability of resources, and fair governance (Gupta et al., 2008). They play a key role in mediating the transformation of coping capacity into adaptive capacity and in linking short and long-term responses to climate change and variability (Berman et al., 2012). Most developing countries have weaker institutions that are less capable of managing extreme events, increasing vulnerability to disasters (Lateef, 2009; Biesbroek et al., 2013). Countries with strong functional institutions are generally assumed to have a greater capacity to adapt to current and future disasters. However, Hurricane Katrina of 2005 in the USA and the European heat wave of 2003 demonstrate that strong institutions and other determinants of adaptive capacity do not necessarily reduce vulnerability if these attributes are not translated to actions (IPCC, 2007a; see also Box 2-1, Section 2.4.2.2).

To facilitate adaptation under uncertainty, institutions need to be flexible enough to accommodate adaptive management processes such as evaluation, learning, and refinement (Agarwal, 2010; Gupta et al., 2010; see also Section 14.2.3). Organizational learning can lead to significant change in organizations' purpose and function (Bartley, 2007), for example, where non-governmental organizations have moved from advocacy to program delivery with local stakeholders (Ziervogel and Zermoglio, 2009; Kolk and Pinkse, 2010; Worthington and Pipa, 2010).

Boundary organizations are increasingly being recognized as important to CIAV decision support (Guston, 2001; Cash et al., 2003; McNie, 2007; Vogel et al., 2007). A boundary organization is a bridging institution, social arrangement, or network that acts as an intermediary between science and policy (Glossary). Its functions include facilitating communication between researchers and stakeholders, translating science and technical information, and mediating between different views of how to interpret that information. It will also recognize the importance of location-specific contexts (Ruttan et al., 1994); provide a forum in which information can be co-created by interested parties (Cash et al., 2003); and develop boundary objects, such as scenarios, narratives, and model-based decision support systems (White et al., 2010). Adaptive and inclusive management practices are considered to be essential, particularly in addressing wicked problems such as climate change (Batie, 2008). Boundary organizations also link adaptation to other processes managing global change and sustainable development.

Boundary organizations already contributing to regional CIAV assessments include the Great Lakes Integrated Sciences and Assessments Center in the USA (GLISA; http://www.glisa.umich.edu/); part of the Regional Integrated Sciences and Assessments Program of the U.S. government (RISA; Pulwarty et al., 2009); the UK Climate Impacts Program (UKCIP; UK Climate Impacts Program, 2011); the Alliance for Global Water Adaptation (AGWA; http://alliance4water.org); and institutions working on water issues in the USA, Mexico, and Brazil (Kirchhoff et al., 2012; Varady et al., 2012).

2.2.2.2. Governance

Effective climate change governance is important for both adaptation and mitigation and is increasingly being seen as a key element of risk management (*high confidence*) (Renn, 2008; Renn et al., 2011). Some analysts propose that governance of adaptation requires knowledge of anticipated regional and local impacts of climate change in a more traditional planning approach (e.g., Meadowcroft, 2009), whereas others propose governance consistent with sustainable development and resilient systems (Adger, 2006; Nelson et al., 2007; Meuleman and in 't Veld, 2010). Quay (2010) proposes "anticipatory governance"—a flexible decision framework based on robustness and learning (Sections 2.3.3, 2.3.4). Institutional decisions about climate adaptation are taking place within a multi-level governance system (Rosenau, 2005; Kern and Alber, 2008). Multi-level governance could be a barrier for successful adaptation if there is insufficient coordination as it comprises different regulatory, legal, and institutional systems (Section 16.3.1.4), but is required to manage the "adaptation paradox" (local solutions to a global problem), unclear ownership of risks and the adaptation bottleneck linked to difficulties with implementation (Section 14.5.3). Lack of horizontal and vertical integration between organizations and policies leads to insufficient risk governance in complex social-ecological systems such as coasts (Section 5.5.3.2) and urban areas (Section 8.4), including in the management of compound risks (Section 19.3.2.4).

Legal and regulatory frameworks are important institutional components of overall governance, but will be challenged by the pervasive nature of climate risks (*high confidence*) (Craig, 2010; Ruhl, 2010a,b). Changes proposed to manage these risks better under uncertainty include integration between different areas of law, jurisdictions and scale, changes to property rights, greater flexibility with respect to adaptive management, and a focus on ecological processes rather than preservation (Craig, 2010; Ruhl, 2010a; Abel et al., 2011; Macintosh et al., 2013). Human security in this report is not seen just as an issue of rights (Box 12-1), given that a minimum set of universal rights exists (though not always exercised), but is instead assessed as being subject to a wide range of forces. Internationally, sea level rise could alter the maritime boundaries of many nations that may lead to new claims by affected nations or loss of sovereignty (Barnett and Adger, 2003). New shipping routes, such as the North West Passage, will be opened up by losses in Arctic sea ice (Sections 6.4.1.6, 28.2.6). Many national and international legal institutions and instruments need to be updated to face climate-related challenges and decision implementation (*medium confidence*) (Verschuuren, 2013).

2.3. Methods, Tools, and Processes for Climate-related Decisions

This section deals with methods, tools, and processes that deal with uncertainties (Section 2.3.1); describes scenarios (Section 2.3.2); covers trade-offs and multi-metric valuation (Section 2.3.3); and reviews learning and reframing (Section 2.3.4).

2.3.1. Treatment of Uncertainties

Most advice on uncertainty, including the latest guidance from the IPCC (Mastrandrea et al., 2010; see also Section 1.1.2.2), deals with uncertainty in scientific findings and to a lesser extent confidence. Although this is important, uncertainty can invade all aspects of decision making, especially in complex situations. Whether embodied in formal analyses or in the training and habits of decision makers, applied management is often needed because unaided human reasoning can produce mismatches between actions and goals (Kahneman, 2011). A useful high-level distinction is between ontological uncertainty—what we know—and epistemological uncertainty—how different areas of knowledge and "knowing" combine in decision making (van Asselt and Rotmans, 2002; Walker et al., 2003). Two other areas of relevance are ambiguity (Brugnach et al., 2008) and contestedness (Klinke and Renn, 2002; Dewulf et al., 2005), commonly encountered in wicked problems/systemic risks (Renn and Klinke, 2004; Renn et al., 2011).

Much of this uncertainty can be managed through framing and decision processes. For example, a predict-then-act framing is different to an assess-risk-of-policy framing (SREX Section 6.3.1 and Figure 6.2; Lempert

et al., 2004). In the former, also known as "top-down," model or impacts-first, science-first, or standard approach, climate or impact uncertainty is described independently of other parts of the decision problem. For instance, probabilistic climate projections (see Figure 21-4 or WGI AR5 Chapters 11 and 12; Murphy et al., 2009) are generated for wide application, and thus are not tied to any specific choice. This follows the cause and effect model described in Section 2.1. The basic structure of IPCC Assessment Reports follows this pattern, with WGI laying out what is known and uncertain about current and future changes to the climate system. Working Groups II and III then describe impacts resulting from and potential policy responses to those changes (Jones and Preston, 2011).

In contrast, the "assess-risk-of-policy" framing (Lempert et al., 2004; UNDP, 2005; Carter et al., 2007; Dessai and Hulme, 2007) starts with the decision-making context. This framing is also known as "context-first" (Ranger et al., 2010); "decision scaling" (Brown et al., 2011); "bottom-up"; vulnerability, tipping point (Kwadijk et al., 2010); critical threshold (Jones, 2001); or policy-first approaches (SREX Section 6.3.1). In engaging with decision makers, the "assess-risk-of-policy" approach often requires information providers work closely with decision makers to understand their plans and goals, before customizing the uncertainty description to focus on those key factors. This can be very effective, but often needs to be individually customized for each decision context (Lempert and Kalra, 2011; Lempert, 2012) requiring collaboration between researchers and users (see Box 2-1). A "predict-then-act" framing is appropriate when uncertainties are shallow, but when uncertainties are deep, an "assess-risk-of-policy" framing is more suitable (Dessai et al., 2009).

The largest focus on uncertainty in CIAV has been on estimating climate impacts such as streamflow or agricultural yield changes and their consequent risks. Since AR4, the treatment of these uncertainties has advanced considerably. For example, multiple models of crop responses to climate change have been compared to estimate inter-model uncertainty (Asseng et al., 2013). Although many impact studies still characterize uncertainty by using a few climate scenarios, there is a growing literature that uses many climate realizations and also assesses uncertainty in the impact model itself (Wilby and Harris, 2006; New et al., 2007). Some studies propagate uncertainties to evaluate adaptation options locally (Dessai and Hulme, 2007) by assessing the robustness of a water company's plan to climate change uncertainties or regionally (Lobell et al., 2008) by identifying which regions are most in need of adaptation to food security under a changing climate. Alternatively, the critical threshold approach, where the likelihood of a given criterion can be assessed as a function of climate change, is much less sensitive to input uncertainties than assessments estimating the "most likely" outcome (Jones, 2010). This is one of the mainstays of robustness assessment discussed in Section 2.3.3.

2.3.2. Scenarios

A scenario is a story or image that describes a potential future, developed to inform decision making under uncertainty (Section 1.1.3). A scenario is not a prediction of what the future will be but rather a description of how the future might unfold (Jäger et al., 2008). Scenario use in the CIAV research area has expanded significantly beyond climate into broader socioeconomic areas as it has become more mainstream (*high confidence*) (Sections 1.1.3, 2.4.2.1). Climate change has also become a core feature of many scenarios used in regional and global assessments of environmental and socioeconomic change (Carpenter et al., 2005; Raskin et al., 2005). Scenarios can be used at a number of stages within an assessment process or can underpin an entire assessment. They serve a variety of purposes, including informing decisions under uncertainty, scoping and exploring poorly understood issues, and integrating knowledge from diverse domains (Parson et al., 2007; Parson, 2008).

Scenarios also contribute to learning and discussion, facilitate knowledge exchange, and can be expressed using a range of media. Local scale visualization of impacts and adaptation measures, depicted on realistic landscapes, is an emerging technology that is being tested to support dialog on adaptation planning at the local scale (Schroth et al., 2011; Sheppard, 2012). Although visual representations of scenario-based impact assessments may be available for a location, scenario-based adaptation assessments usually are not. Artistic depictions of potential adaptation measures and outcomes are being negotiated and assessed with local stakeholders in communities within Metro Vancouver, Canada (Shaw et al., 2009; Burch et al., 2010; Sheppard et al., 2011).

Climate, socioeconomic, or other types of scenarios are widely used to assess the impacts of climate change. Fewer studies report on the use of scenarios as participatory tools to enable decision making on adaptation (e.g., Harrison et al., 2013). However, the scenario literature emphasizes the importance of process over product. The new generation of climate and socioeconomic scenarios being developed from the Representative Concentration Pathways (RCPs; 1.1.3.1) and Shared Socioeconomic Pathways (SSPs; 1.1.3.2), which are storylines corresponding to the new RCPs (Moss et al., 2010; Kriegler et al., 2012) have yet to be applied within CIAV studies in any substantive way (van Ruijven et al., 2013; Ebi et al., 2014).

By separating risks into simple and systemic or wicked-problem risks, scenario needs for decision making can be better identified (*medium confidence*). For simple risks, if probabilities cannot be easily calculated then scenarios can be used to explore the problem, test for acceptable or unacceptable levels of risk, and illustrate alternative solutions for evaluation and testing. Wicked problems will need to be thoroughly scoped to select the most suitable decision-making process, with scenarios playing an important role. They may require separate applications of problem (exploratory or descriptive) and solution-based (normative or positive) scenarios or the development of reflexive scenarios, the latter being updated with new knowledge over time that may re-examine values and goals (van Notten, 2006; Wilkinson and Eidinow, 2008; Jones, 2012); these categories can also be structured as top-down, bottom-up, and interactive (Berkhout et al., 2013). Even if conditional probabilities can be used to illustrate climate futures, scenarios are needed to explore the solutions space involving strategic actions, options planning, and governance using process and goal-oriented methods (*high confidence*).

2.3.3. Evaluating Trade-offs and Multi-metric Valuation

Decision makers bring diverse aims, interests, knowledge, and values to CIAV decision making. With effective decision support, parties to a

decision can manage competing views by more clearly articulating their goals; understanding how various options affect trade-offs between goals; and making informed choices that participants regard as legitimate, salient, and credible (*high confidence*) (Cash et al., 2003). The decision theory, risk governance, and ethical reasoning literatures use two broad sets of criteria for decision making: outcome-based criteria focus on whether a decision is likely to meet specified goals; process-based criteria compare alternative actions according to the process by which a decision is arrived. In particular, decision process aims to help stakeholders choose between the risks, costs, and obligations being proposed (Morgan et al., 1990), including specified levels of risk tolerance. Such choices around risk tolerance, including acceptable levels of risk, are ethical choices (DesJardins, 2012; Nanda, 2012). Selection strategies informing context and process are described in Section 14.3.5. Decision criteria inform the discussions of adaptation options, planning, and economics in Chapters 14 to 17 and WGIII AR5 Chapter 2.

Multi-attribute decision theory (Keeney and Raiffa, 1993), or multi-criteria decision analysis (MCDA), provides the most general framework for assessing outcomes-based criteria. MCDA concepts and tools organize and display the implications of alternative decisions on differing objectives (e.g., cost and environmental quality), order and test preferences among trade-offs between potentially incommensurate objectives, and show how alternative processes for choosing options can lead to different decisions. Cost-benefit analysis under uncertainty, one key tool for evaluating trade-offs, is described in Section 17.3.2.1. Simple MCDA tools include scorecards that graphically display how alternative policy choices affect different goals. For example, the "burning embers" diagram displays how risks to various attributes (e.g., health of unique systems, extreme weather events) depend on targets for a given global mean temperature increase (Figure 19-5). More sophisticated MCDA tools can optimize a portfolio of choices in a variety of ways; for example, one recent method applies scenarios representing significant uncertainty to optimize between four or more choices in order to identify robust combinations and system vulnerabilities (Kasprzyk et al., 2013). Successful use of MCDA in CIAV decisions include the U.S. Bureau of Reclamation helping stakeholders with diverse interests and values to consider 26 alternative performance measures for the Colorado River system, to agree on potential climate-related risks, and to consider options for reducing those risks. Trade-offs also occur where adaptation measures produce negative impacts in other areas of value—for example, where adaptation in agricultural and urban areas negatively affect ecosystems (Section 4.3.3.3). Korteling et al. (2013) assess the robustness of adaptation options for six criteria including risk of water shortage, environmental impact, local self-sufficiency, cost, carbon footprint, and social acceptability. Chapter 17 describes many criteria commonly used in MCDA analyses.

Robustness is often nominated as the most appropriate criterion for managing large decision uncertainty. It is a satisficing (sufficient rather than optimal) criterion (Rosenhead, 1989) that seeks decisions likely to perform well over a wide range of plausible climate futures, socioeconomic trends, and other factors (Dessai and Hulme, 2007; Groves et al., 2008; Wilby and Dessai, 2010; WUCA, 2010; Brown et al., 2011; Lempert and Kalra, 2011). Robust decisions often perform better than other methods if the future turns out differently than expected. Testing for robustness can often illuminate trade-offs that help decision makers achieve consensus even when they have different future expectations. Robust choices often trade some optimality for being able to manage unanticipated outcomes. Many forms of the precautionary principle are consistent with robustness criteria (Lempert and Collins, 2007). Flexible and reversible options are often needed to manage situations with significant potential for unanticipated outcomes and differences in values and interests among decision makers (Gallopín, 2006; Hallegatte, 2009; see also Sections 2.3.4, 5.5.3.1). Flexibility is signaled by reaching of specific management thresholds, critical control points, or design states (Box 5-1). The literature disagrees on the relationship between robustness and resilience (Folke, 2006). Chapter 20 describes resilience as a property of systems that might be affected by decision makers' choices, while robustness is a property of the choices made by those decision makers (SREX Chapter 1).

Process-based criteria focus on the credibility and legitimacy of a decision process. Institutional (Section 2.2.2) and cultural and ethical (Section 2.2.1) contexts will strongly influence the appropriateness and importance of such criteria in a given situation (*high confidence*). Process criteria provide institutional rules, and governance for decision making in a wide range of circumstances (Dietz and Stern, 2008; Sen, 2009). For instance, many environmental laws require advanced notice and periods of public comment before any regulations are issued. Water rights can be made tradable, giving users extra flexibility during times of water shortage or oversupply. Participants may regard any decision that fails to respect such rights as illegitimate. In complex situations of a collaborative nature, both outcome and process-related criteria will be needed in a decision-making process (*high confidence*).

Stakeholder involvement is a central process for climate-related decision making and since the AR4 has grown in importance, particularly for adaptation decision making (e.g., Lebel et al., 2010), covering methods (Debels et al., 2009; Gardner et al., 2009; Salter et al., 2010; André et al., 2012) and reflecting concrete experiences with stakeholder involvement in CIAV assessments and adaptation processes (de la Vega-Leinert et al., 2008; Ebi and Semenza, 2008; Posthumus et al., 2008; Raadgever et al., 2008; Tompkins et al., 2008a,b; Preston et al., 2009). Lebel et al. (2010) differentiate six advantages of social learning and stakeholder involvement for adaptation to climate change: (1) reduces informational uncertainty; (2) reduces normative uncertainty; (3) helps to build consensus on criteria for monitoring and evaluation; (4) can empower stakeholders to influence adaptation and take appropriate actions themselves by sharing knowledge and responsibility in participatory processes; (5) can reduce conflicts and identify synergies between adaptation activities of various stakeholders, thus improving overall chances of success; and (6) can improve the likely fairness, social justice, and legitimacy of adaptation decisions and actions by addressing the concerns of all relevant stakeholders. Complex settings will require a detailed mapping of stakeholder roles and responsibilities (André et al., 2012).

2.3.4. Learning, Review, and Reframing

Effective decision support processes generally include learning, where learning and review become important to track decision progress (National Research Council, 2009b; see also Box 2-1, Figure 2-1). This can be achieved by developing an ongoing monitoring and review process

Frequently Asked Questions

FAQ 2.2 | Which is the best method for climate change decision making/assessing adaptation?

No single method suits all contexts, but the overall approach used and recommended by the IPCC is iterative risk management. The International Standards Organization defines risk as the effect of uncertainty on objectives. Within the climate change context, risk can be defined as the potential for consequences where something of human value (including humans themselves) is at stake and where the outcome is uncertain. Risk management is a general framework that includes alternative approaches, methodologies, methods, and tools. Although the risk management concept is very flexible, some methodologies are quite prescriptive—for example, legislated emergency management guidelines and fiduciary risk. At the operational level, there is no single definition of risk that applies to all situations. This gives rise to much confusion about what risk is and what it can be used for.

Simple climate risks can be assessed and managed by the standard methodology of making up the "adaptation deficit" between current practices and projected risks. Where climate is one of several or more influences on risk, a wide range of methodologies can be used. Such assessments need to be context-sensitive, to involve those who are affected by the decision (or their representatives), to use both expert and practitioner knowledge, and to map a clear pathway between knowledge generation, decision making, and action.

during the scoping stage of a project or program. If circumstances change so much that desired outcomes may not be achieved, then reframing of the decision criteria, process, and goals may be required. This iterative approach begins with the many participants to a decision working together to define its objectives and other parameters, working with experts to generate and interpret decision-relevant information, then revisiting the objectives and choices based on that information (Figure 2-1). Again, process is important. Pelling et al. (2008) found that accounting for different personal values in both an official and informal capacity could enhance social learning and therefore adaptive capacity. Measuring progress on adaptation and adaptive capacity by tracking impacts, vulnerability, and related adaptation metrics and process indicators is discussed in Section 14.6. Such metrics are needed to transfer wider learning on adaptation to new situations.

Learning and review can range from periodic reporting to adaptive management. Adaptive management refers to a choice of policy required to generate reliable new information (Holling, 1978, 1996) and involves a process of adjusting approaches in response to observations of their effect and changes in the system brought on by resulting feedback effects and other variables (Glossary). Adaptive strategies are designed to be robust over a wide range of futures by evolving over time in response to new information (Rosenhead, 1989; Walker et al., 2001; Lempert and Schlesinger, 2002; Swanson et al., 2006). Necessary components include separating immediate actions from those that can be deferred (and that may require additional information); an explicit process to generate new information; institutional mechanisms for incorporating and acting on new information; and some understanding of the policy limits that, if exceeded, should lead to its re-evaluation (Swanson et al., 2012; see also Box 5-1). As indicated by Figure 2-1, effective decision making not only requires flows of appropriate information but people willing and able to act on it. Though most policies change over time, very few follow the steps of an intentional adaptive strategy (*high confidence*). For instance, McCray et al. (2010) surveyed 32 examples of U.S. environmental, health, and safety regulations—all legally required to be adaptive—and found only five instances where any policy change occurred as intended.

Reframing of an action can occur when an existing set of decisions and actions are failing to manage risks adequately (see Box 2-1). Based on experience to date, there now exists a sufficiently rich set of available methods, tools, and processes to support effective CIAV decisions in a wide range of contexts (*medium confidence*), although they may not be combined appropriately, accessible, or readily used by decision makers (Webb and Beh, 2013). Tools for decision making, planning and development, and transfer and diffusion are discussed in Section 15.4.

2.4. Support for Climate-related Decisions

Growing understanding of the aspects of decision making (Section 2.2) and methods and tools (Section 2.3) have led to improved support for CIAV decisions, as shown by the provision of climate information and services (Section 2.4.1), methods for impacts and vulnerability assessments (Section 2.4.2), and decision support in practice (Section 2.4.3). Figure 2-3 divides the decision-making process into four stages: scoping, analysis, implementation and review, outlining institutional, leadership, knowledge, and information characteristics for each stage. Most effort in CIAV research has been put into the first two stages, whereas decision implementation and follow-up have been minimal. This does not imply that the analysis stage is discounted. Problem analysis and solution evaluation are significant undertakings in any decision process, but that is where most current climate change assessments stop. Note that each of these stages can be divided into other quite distinct process elements.

2.4.1. Climate Information and Services

Climate services are institutions that bridge generation and application of climate knowledge. History and concepts are described in Section

Box 2-1 | Managing Wicked Problems with Decision Support

A well-designed decision support process, combined with favorable political conditions, can effectively address "wicked" (Section 2.1) decision challenges. The State of Louisiana faces a serious problem of coastal land loss, exposing the region's fisheries and heightening the risk of storm surge damage to the City of New Orleans, one of the USA's largest ports with facilities that account for ~20% of U.S. oil and gas production (Coastal Protection and Restoration Authority, 2007). Previous efforts at comprehensive coastal protection had been stymied by, among other factors, numerous competing jurisdictions and stakeholders with a wide range of conflicting interests.

In the aftermath of Hurricane Katrina, the state embarked on a new coastal planning effort, this time with extensive decision support. The Coastal Protection and Restoration Authority organized an extension decision support effort with a network of research institutions interacting with a 33-member stakeholder group consisting of representatives from business and industry; federal, state, and local governments; non-governmental organizations; and coastal institutions. In dozens of workshops over the course of 2 years, these stakeholders influenced the development of and interacted with a decision support system consisting of (1) a regional model that integrated numerous strands of scientific data into projections of future flood risk (Fischbach et al., 2012) and (2) a multi-attribute planning tool that allowed stakeholders to explore the implications of alternative portfolios of hundreds of proposed risk reduction projects over alternative sea level rise scenarios (Groves et al., 2012). This decision support system allowed decision makers and stakeholders to first formulate alternative risk reduction plans then to visualize outcomes and trade-offs up to 50 years into the future.

The resulting Master Plan for a Sustainable Coast passed the state legislature by a unanimous vote in May 2012. Deviating strongly from past practice, the plan allocates far more resources to restoring natural barriers than to structural measures such as levees. The plan balances the interests of multiple stakeholders and contains some projects that offer near-term benefits and some whose benefits will be largely felt decades from now. Observers recognized that extensive analytic decision support contributed significantly to this plan.

2.4.1.1, how decision support applied in Section 2.4.1.2, and the policy implications of climate services as a global practice in Section 2.4.1.3. These institutions supply climate information on local, regional, national, and global scales for the monitoring of risks, mitigation, and adaptation planning as an important component of sustainable development (Sivakumar et al., 2011). The Global Framework for Climate Services (Hewitt et al., 2012) aims to "enable better management of the risks of climate variability and change and adaptation to climate change, through the development and incorporation of science-based climate information and prediction into planning, policy, and practice on the global, regional, and national scale" (http://www.wmo.int/pages/gfcs/index_en.php). Climate services focus on the connection between climate science and the public demand for information; however, their development and deployment needs support from many other disciplines (Miles et al., 2006). This extended reach requires measures such as case-specific communication, engagement, and knowledge exchange skills (*high confidence*).

While many countries have already established national and regional climate services or are on the way to doing so, they show significant differences. The development of Regional Climate Services in the USA and parts of Europe, with their increasing focus on communication and decision support, is well documented (DeGaetano et al., 2010; von Storch et al., 2011). Developing countries are becoming increasingly aware of the need for climate services (Semazzi, 2011), which is in part reflected in the migration of regional climate models into those countries. In 2001 only around 21 (mostly Organisation for Economic Co-operation and Development (OECD)) countries were running regional climate models (RCMs), but today more than 100 countries are trained in using the Providing REgional Climates for Impact Studies (PRECIS) RCM (Jones et al., 2004; Edwards, 2010). Regional climate services are expanding geographically, shifting from simple understandings of climate cause and effect to ever more complex and wicked problem situations and are becoming more interdisciplinary.

2.4.1.1. Climate Services: History and Concepts

Early climate services in North America were seen as an expansion of weather services, dealing mainly with forecasts, seasonal outlooks, and risk assessment in a mostly stationary but variable climate (Changnon et al., 1990; Miles et al., 2006; DeGaetano et al., 2010). This mainly technical outlook had limited effectiveness; for example, decision makers had difficulties understanding and using climate data for planning purposes (Changnon et al., 1990; Miles et al., 2006; Visbeck, 2008) and the data were slow to access and of poor quality (Changnon et al., 1990). As these services developed, formal definitions of their mission and scope shifted to being user-centric, focusing on active research, data stewardship and effective partnership (National Research Council, 2001). Climate services were understood as a clearinghouse and technical access point to stakeholders, providing education and user access to experts—the latter informing the climate forecast community of information needs, largely to inform adaptation (Miles et al., 2006).

Downscaling is a key product demanded by users for decision making (Section 21.3.3.2). For example, in Africa, regional climate models play an increasing role in Regional Climate Outlook Forums arranged by the

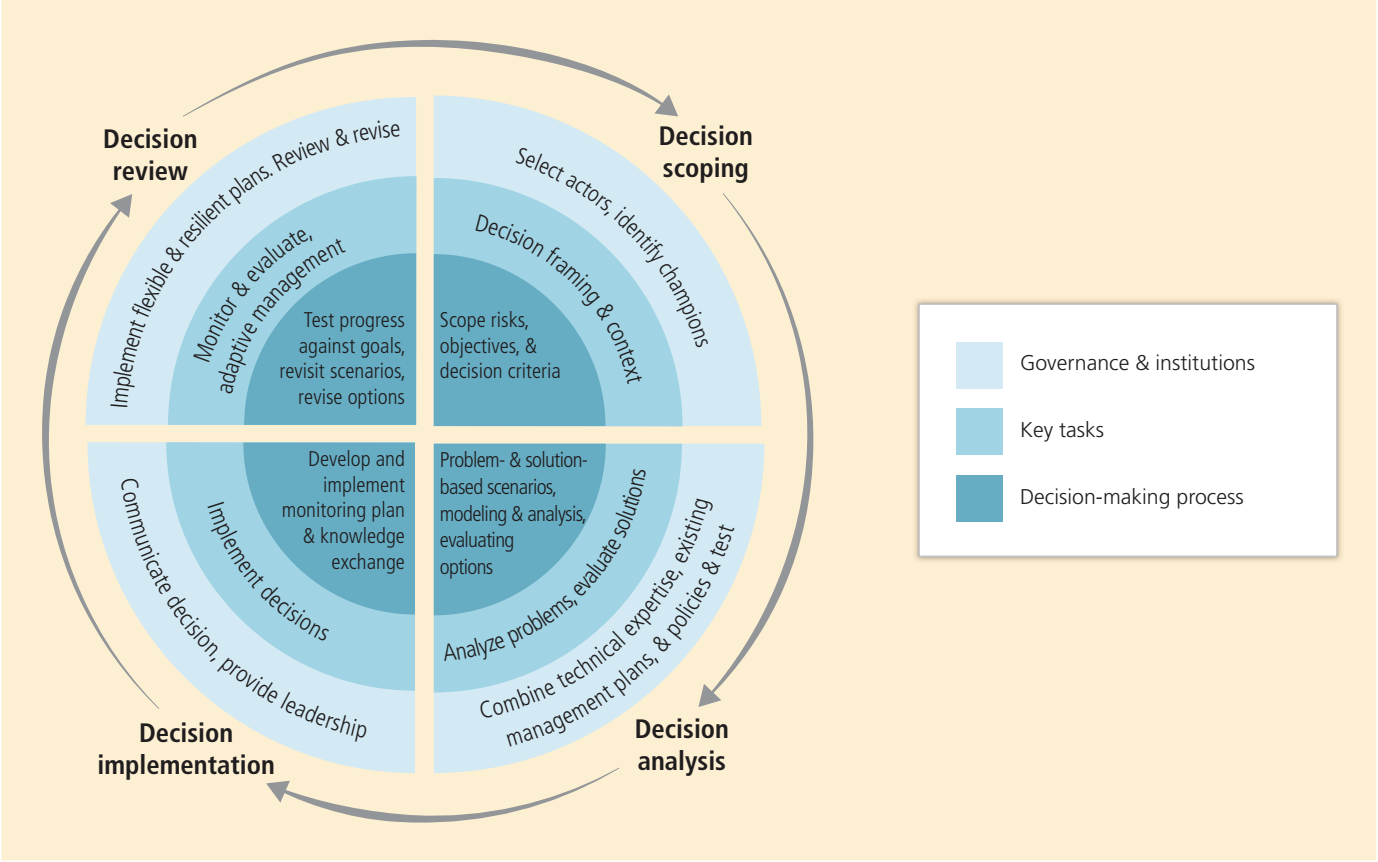


Figure 2-3 | Four-stage process of decision making. Note that while adaptive management is located in the decision review quadrant here, when applied it will influence the entire process.

World Meteorological Organization (WMO). The Global Framework for Climate Services was created in order to coordinate and strengthen activities and develop new infrastructure where needed, focusing on developing countries (WMO, 2011; Hewitt et al., 2012). From initially being supply-focused and static, public climate services increasingly need communication skills, engagement, and knowledge exchange in a highly challenging environment of technical and institutional networks, monitoring systems, and collaborations with other institutions, stakeholders, and decision makers (DeGaetano et al., 2010).

2.4.1.2. Climate Services: Practices and Decision Support

Decision support is generally acknowledged as an integral part of climate services (*high confidence*) (Miles et al., 2006; DeGaetano et al., 2010). Depending on the stage and context in question (see Section 2.1.3.), "best" data as framed by experts should be reconciled with user needs in order to produce scientific information that is relevant and suitable for decision making. Social and cultural determinants have to be taken into account (see Section 2.2) and require the communication of scientific data to be context-specific. Decision support for climate services consists of "processes of interaction, different forms of communication, potentially useful data sets or models, reports and training workshops, data ports and websites, engaging any level of governance, at any stage in the policy- or decision-making process" (Moser, 2009, p. 11). The climate service is a "process of two-way communication" and "involves providing context that turns data into information" (Shafer, 2004). Capacity building is required on all sides of the communication process. For regional climate services, a successful learning process engages both users and providers of knowledge in knowledge exchange. For example, the uptake and utility of climate forecasts in rural Africa is described in Box 9-4.

As knowledge brokers, climate services have to establish an effective dialog between science and the public (von Storch et al., 2011). This dialog undertakes two main tasks: One is to understand the range of perceptions, views, questions, needs, concerns, and knowledge in the public and among stakeholders about climate, climate change, and climate risks; the other task is to convey the content of scientific knowledge to the public, media, and stakeholders. This includes communicating the limitations of such knowledge, the known uncertainties, and the unknowable, as well as the appropriate role of science in complex decision processes (von Storch et al., 2011).

2.4.1.3. The Geo-political Dimension of Climate Services

Climate knowledge is continually being documented and assessed by the social sciences within a policy-relevant context (Yearley, 2009; Grundmann and Stehr, 2010). One focus is on the spread of climate knowledge into developing countries. Climate models distributed to users with no in-house capacity for model development build capacity in

regional climate science, producing high-resolution data for local decision making. This mobility of knowledge has far-reaching implications for how climate knowledge is produced; strengthening the influence of epistemic communities such as the IPCC and other global governance mechanisms (Mahony and Hulme, 2012). Thus, while regional climate models play an increasingly important role in decision-making processes, critics argue that climate monopolizes planning and development strategies, rendering other forms of knowledge subordinate to this "climate reductionism" (Dessai et al., 2009; Hulme, 2011).

Indigenous forms of knowledge—including the specialized knowledge of any stakeholder—are becoming increasingly relevant for climate services (*high confidence*) (Strauss and Orlove, 2003; Crate and Nuttal, 2009; Crate, 2011; Ulloa, 2011; Krauss and von Storch, 2012). Local forms of knowledge and scientific climate models are not necessarily mutually exclusive; individual case studies show how both forms of knowledge contribute jointly to place-based adaptation (Strauss and Orlove, 2003; Orlove and Kabugo, 2005; Orlove, 2009; Strauss, 2009; Orlove et al., 2010). Indigenous knowledge in the form of oral histories and other traditional knowledge are being compared or combined with remote sensing technologies and model-based scenarios to co-produce new knowledge, and to create a new discourse on adaptation planning (Nakashima et al., 2012; see also Table 15-1). The challenge will be to collaborate in a way that enables their integration into a shared narrative on future adaptation choices.

These examples show that adaptation needs both to be implemented locally and to be informed by larger scale (inter-)national policies and directions. One strategy will not suit every location. Endfield (2011) argues for a "reculturing and particularizing of climate discourses" in order to successfully localize global and scientific meta-narratives. Climate service development combines very different types of knowledge and the social, cultural, and communication sciences play a decisive role in this process (Pidgeon and Fischhoff, 2011; von Storch et al., 2011). To position itself and to react according to the diverse demands, science-based climate services have to become "rooted in society" (Krauss, 2011). The climate science community does not necessarily take the lead, but becomes part of an inter- and trans-disciplinary process, where politics, culture, religion, values, and so forth become part of climate communication (*medium confidence*).

2.4.2. Assessing Impact, Adaptation, and Vulnerability on a Range of Scales

CIAV assessments address the "adapt to what" question, which can enable a dialog among practitioners, stakeholders, and the public on planning and implementation of adaptation measures within prevailing mechanisms for governance. To date, however, assessments have focused more on I than A (see Figure 1-1d). A number of global initiatives are taking place to enable knowledge generation, transfer, and use, including the Programme of Research on Climate Change Vulnerability, Impacts and Adaptation (PROVIA; http://www.provia-climatechange.org/), the Nairobi Work Programme on impacts, vulnerability, and adaptation to climate change (http://unfccc.int/adaptation/nairobi_work_programme/items/3633.php), and work by the World Bank and regional development banks (http://climatechange.worldbank.org/).

2.4.2.1. Assessing Impacts

For scenario-based impact assessments to contribute to vulnerability and risk assessment, a series of translations need to be performed. Scenarios of projected GHG concentrations are converted to changes in climate, impacts are assessed, perhaps with autonomous adaptation, leading to the evaluation of various adaptation options. This series of translations requires the transformation of data across various scales of time and space, between natural and social sciences, utilizing a wide variety of analytical tools representing areas such as agriculture, forestry, water, economics, sociology, and social-ecological systems. Climate scenarios are translated into scenarios or projections for biophysical and socioeconomic impact variables such as river flow, food supply, coastal erosion, health outcomes, and species distribution (e.g., European Climate Adaptation Platform, http://climate-adapt.eea.europa.eu). Climate services help establish and support the translation process (Section 2.4.1).

The resulting climate impacts and risks are then subject to decision making on risk management and governance. Assessments of observed events combine biophysical and socioeconomic assessments of the past and present (Table 2-1, top row). Most scenario-based assessments superimpose biophysical "futures" onto present-day socioeconomic conditions (Table 2-1, middle row). This is useful for assessing how current socioeconomic conditions may need to change in response to biophysical impacts but raises inconsistencies when future socioeconomic states are out of step with biophysical states. This will hamper assessments of future adaptation responses in coupled social-ecological systems (see Chapter 16). An important challenge, therefore, is to construct impact assessments in which biophysical futures are coupled with socioeconomic futures (Table 2-1, bottom row). A new set of socioeconomic futures, known as Shared Socioeconomic Pathways (SSPs), which are storylines corresponding to the new RCPs (Moss et al., 2010; Kriegler et al., 2012), is being developed to assist this process (Section 1.1.3.2).

A new generation of assessments links biophysical, economic, and social analysis tools in order to describe the interactions between projected biophysical changes and managed systems. For example, Ciscar et al. (2011) estimated the costs of potential climate change impacts, without public adaptation policies, in four European market sectors (agriculture, river floods, coastal areas, and tourism) and one nonmarket sector

Table 2-1 | Nature of published Impact, Adaptation, and Vulnerability (IAV) assessments.

Nature of IAV assessments	Biophysical conditions	Socioeconomic conditions
Stationarity and extrapolation	Continuation of current trends; no change in statistical properties	No change from current conditions
Transitional	Scenario-based projections of future biophysical conditions	No change from current conditions; sometimes sensitivity analysis with alternate futures
Coupled and interactive	Scenario-based projections of future biophysical conditions	Alternative futures from scenarios/storylines consistent with biophysical projections, sometimes with dynamic response

(human health). A similar study in the UK was conducted for tourism, health and transportation maintenance, buildings and transportation infrastructure, and residential water supplies (Hunt, 2008). In the USA, Backus et al. (2013) assessed national and state level gross domestic product (GDP) and employment impacts, incorporating direct impacts on water resources, secondary impacts on agriculture and other water interests, and indirect impacts through interstate migration of affected populations. Decision support tools are being integrated into scenario-based impact and adaptation assessments. For example, the Water Evaluation and Planning System model has been used to assess a community water system in British Columbia, Canada (Harma et al., 2012). Incorporation of stakeholder dialog processes within scenario construction (Parson, 2008) and Participatory Integrated Assessment (Salter et al., 2010) enables inclusion of local knowledge as part of scenario-based assessments.

2.4.2.2. Assessing Vulnerability, Risk, and Adaptive Capacity

The adaptation to climate change, disaster risk management, and resilience literatures all address the concept of vulnerability, defined as a susceptibility to loss or damage (Adger, 2006; Füssel, 2007), or the propensity or predisposition to be adversely affected (Glossary). Within IPCC AR4, Schneider et al. (2007) identified vulnerabilities that might be considered "key," and therefore potentially "dangerous" (see Glossary). Criteria denoting a key vulnerability include its magnitude and timing, persistence, and reversibility, and the likelihood and confidence that the contributing event(s) would occur (Sections 19.2.5, 19.6). Other criteria include the importance of a location or activity to society and society's exposure to potential loss and its capacity to adapt. Adaptive capacity has been defined as the ability to adjust, to take advantage of opportunities, or to cope with consequences (Adger et al., 2007; see also Glossary). However, adaptive capacity is context-specific, related to both availability of resources, capacity to learn, and governance measures (Gupta et al., 2010; see also Section 14.5). Actions that illustrate how adaptive capacity and climate resilience can be mutually reinforcing include disaster risk management (Sections 2.5.2, 15.3.2, 16.7.2) and "triple-win" interventions where adaptation, mitigation, and sustainable development goals are integrated so as to find climate-resilient pathways (Sections 20.3.3, 20.4.2).

The concept of an "adaptation deficit" (Burton and May, 2004) is applicable to cases such as Hurricane Katrina (Committee on New Orleans Regional Hurricane Protection Projects, 2009; Freudenberg et al., 2009; Box 2-1) or the 2003 European heat wave (Haines et al., 2006) where substantial vulnerability follows a climate event. An adaptation deficit represents a gap between an existing state of adaptation and an idealized state of adaptation where adverse impacts are avoided (Chapter 17; Glossary). The adaptation deficit has also been related to "residual impacts," which occur due to insufficient adaptation to current or future climate (IPCC, 2007a). Within developing countries, Narain et al. (2011) consider the adaptation deficit as being part of a larger "development deficit." Cardona et al. (2012) cite other "deficit" indicators, including a Disaster Deficit Index (extreme event impact combined with financial ability to cope), structural deficit (low income, high inequality, lack of access to resources, etc.), and a risk communication deficit. Maladaptation occurs where a short-term response inadvertently leads to an increase in future vulnerability (Glantz, 1988; Barnett and O'Neill, 2010; McEvoy and Wilder, 2012). Barriers unrelated to scientific knowledge can hamper effective decision making (Adger and Barnett, 2009; Berrang Ford et al., 2011). This may help to explain why some extreme events create surprising levels of damage within developed countries.

The assessment of potential future damages and loss requires approaches that link biophysical and socioeconomic futures. An example is the assessment of climate change effects on human health, including research-to-decision pathways, monitoring of social vulnerability indicators and health outcomes (English et al., 2009; Portier et al., 2010), and tools for enabling adaptive management (Hess et al., 2012). Examples of regional scale scenario-based vulnerability assessments are case studies for North Rhine-Westphalia in Germany (Holsten and Kropp, 2012) and agriculture in Mexico (Monterroso et al., 2012). An example of a larger scale study is a vulnerability assessment of ecosystem services for Europe, in which future adaptive capacity was based on indicators from the *Special Report on Emission Scenarios* (SRES) storylines (Metzger and Schröter, 2006). Difficulty in separating the relative influences of changing climate and development patterns hampers assessments of observed trends in property damage caused by atmospheric extreme events. Recent increases in economic losses may be due to changes in probabilities of extreme events, changes in human development patterns (more people in harm's way) without changes in climatic extremes, or a combination of both (Pielke, 1998; Mills, 2005; Munich Re Group, 2011). IPCC (2012) concluded that increasing exposure has been the major cause, but a role for climate change has not been excluded.

Development choices taken in the current or near term can potentially influence future vulnerability to projected climate change, hence interest in the study of emergent risks (Sections 19.3, 19.4). Interactions between development pathways, and climate change impacts and responses, could create situations with little or no precedent. Assessments based on gradual shifts in mean conditions could underestimate future risk and consequent damage, suggesting the need for process-based methodologies that focus on enhancing resilience (Jones et al., 2013; see also Sections 2.5.2, 20.2.3). An example of assessing this type of risk, and the costs and benefits of potential adaptation responses, is a resilience assessment framework for infrastructure networks (Vugrin et al., 2011; Turnquist and Vugrin, 2013).

2.4.3. Climate-Related Decisions in Practice

Implementation of adaptation actions, resilience strategies and capacity building can take place as stand-alone actions or be integrated into other management plans and strategies. Recent literature on potential climate change effects on natural resources, public health, and community planning and management is reviewed in Chapters 3 to 12. As the complexity of management challenges increases due to climate change, development, and other pressures, a range of reflexive decision-making processes are emerging under the general topics of adaptive management, iterative risk management, and community-based adaptation (e.g., Section 5.5.4.1). However, there are few assessments of adaptation delivery and effectiveness (Section 15.6). Cross-sectoral integrated approaches such as Integrated Water Resources Management (IWRM),

sustainable forestry management (SFM), and Integrated Coastal Zone Management (ICZM) are viewed as being more effective than stand-alone efforts (Section 16.5.1).

Adaptive approaches to water management can potentially address uncertainty due to climate change (Section 3.6.1) but there is a limited number of examples in practice (Section 3.6.4). Examples of recent strategies include an IWRM roadmap prepared for the state of Orissa, India (Jønch-Clausen, 2010) and seven cases in the USA (Bateman and Rancier, 2012), some of which are applying adaptive water management using a scenario-based experimental approach intending to align with IWRM and promote resilience. Adaptations in urban systems following integrated urban water management principles are becoming widespread (Section 8.3.3.4) and in rural systems are more advanced in developed countries and less so in developing countries, especially those within transboundary basins (Sections 9.4.3.2, 24.4.1.5, 24.4.2.5, 25.5.3, 26.3.3, 27.3.1.2, 27.3.2.2).

Adaptation in agriculture ranges from small adjustments made to current activities through to transformative adaptations across whole systems (Sections 7.5.1, 9.4.3.1, 22.4.5.7, 23.4.1, 24.4.4.5, 25.7.2, 26.5.4, 27.3.4.2). Diversified systems are more resilient with some diversification coming from off farm sources (Section 9.4.3.1). There are few unequivocal adaptations to climate, but the development of adaptive capacity is more widespread (Section 7.5.1.2). Adaptation in forestry has expanded since the AR4 (Section 9.4.3.3) and is aiming to develop toward SFM by focusing on biological diversity, productive and protective functions of forests, maintenance of their social and economic benefits, and governance (McDonald and Lane, 2004; Wijewardana, 2008; Montréal Process, 2009). Although SFM is still largely an abstract concept (Seppälä et al., 2009), managing climate change risks is seen as necessary for achieving its objectives (Montréal Process, 2009). Governments and companies are also considering assisted migration of forest species as an adaptation strategy (Pedlar et al., 2012) and payment for ecosystem services is becoming more common (Section 9.4.3.3). Sustainable Fisheries Management has long-term ecological and productivity goals (FAO, 2013) but climate change has generally not been included in strategic guidance for fisheries management (Brander, 2010). Ecosystem-based approaches to management (e.g., Zhou et al., 2010) and transformative approaches will be required (Sections 7.5.1.1.2, 9.4.3.4). Sustainable livelihoods approaches are also being applied for populations dependent on marine resources (Sections 9.4.3.4, 30.6.2.1; Table 30-2).

National Adaptation Programmes of Action (NAPA) for least-developed countries (LDCs) are designed to be flexible, action-oriented, and country-driven (UNFCCC, 2009). Key preparatory steps include the synthesis of available information on vulnerability and impacts via extensive public participation (see Chapter 14). The NAPA process has assisted LDCs to assess climate sensitive sectors and prioritize projects to address the most urgent adaptation issues (Lal et al., 2012; UNFCCC, 2012). Integrating NAPAs with other socioeconomic programs can help develop resilience. However, although many countries have linked their NAPAs with development programs, Hardee and Mutunga (2010) argue that they have had limited success in aligning the NAPA priorities with existing national priorities such as population growth. To this end, scaling up and institutionalization of the NAPA process has commenced. Under the Cancun Adaptation Framework, a process was established that enables LDCs to formulate and implement National Adaptation Plans (NAPs) building upon the NAPA experience (UNFCCC, 2013). The NAP's main objectives are to identify vulnerabilities and medium- and long-term adaptation needs, and to develop and implement strategies and programs to address those needs and also to mainstream climate change risks. The NAPs are also an opportunity to align with other global initiatives such as the Millennium Development Goals and Hyogo Framework for Action.

Many developed countries are developing adaptation strategy documents at different scales of governance (European Environmental Agency, 2013). Biesbroek et al. (2010) analysed National Adaptation Strategies (NAS) of nine European nations, examining their decision making aspects and finding both "top-down" and "bottom-up" (delegation of authorities to local governments) approaches. Dissemination of information on weather, climate, impacts, vulnerability, and scenarios was found to be a critical element for adaptation decision making.

Climate risk is being increasingly factored into existing decision-making processes (Section 15.2.1). For example, learning from the 2003 heat waves that killed some 35,000 people across Europe, many European countries have implemented health-watch warning systems (Alcamo et al., 2007; WHO, 2008). Vietnam has initiated large-scale mangrove restoration and rehabilitation programs with the support of international institutions to protect coastal settlements and aquaculture industry (World Resources Institute et al., 2011). The Tsho Rolpa glacier lake in Nepal was at the risk of outburst due to glacial melt (Adger et al., 2007) so the Government of Nepal introduced both short- and long-term measures to prevent the outburst flood event (World Resources Institute et al., 2011). In many ways, local government is at the coal face of adaptation decision making (Pelling et al., 2008; Measham et al., 2011; Roberts et al., 2012). Municipal governments are incorporating climate change adaptation planning within municipal planning instruments, including energy and water system design, disaster risk reduction, and sustainability plans (Ford and Berrang-Ford, 2011; Rosenzweig et al., 2011). In human health, two main areas of benefit are occurring through improvements in current health patterns being exacerbated by changing climate and in reducing pollutants associated with co-pollutants of GHG emissions (Sections 11.7, 11.9). Climate is being increasingly recognized as a component of human conflict and insecurity, so is becoming a factor in governance arrangements affecting security and peace building programs (Section 12.5).

Details of adaptation planning within urban and rural settlements are addressed in Chapters 8 and 9, respectively. In urban settlements, adaptations are occurring in areas of energy, water, transport, housing, and green infrastructure (Section 8.3.3) but opportunities for broader integration into planning and the urban economy are largely being missed (Section 8.4). The overall status of adaptation implementation is assessed in Chapter 15. Although there is a rapidly growing list of adaptation plans being generated at multiple scales, an evaluation of adaptation plans from Australia, UK, and the USA suggests they are under-developed (Berrang Ford et al., 2011). These plans reflect a preference for capacity building over delivery of specific vulnerability-reduction measures, indicating that current adaptation planning is still informal and ad hoc (Preston et al., 2011; Bierbaum et al., 2013).

Frequently Asked Questions

FAQ 2.3 | Is climate change decision making different from other kinds of decision making?

Climate-related decisions have similarities and differences with decisions concerning other long-term, high-consequence issues. Commonalities include the usefulness of a broad risk framework and the need to consider uncertain projections of various biophysical and socioeconomic conditions. However, climate change includes longer time horizons and affects a broader range of human and Earth systems as compared to many other sources of risk. Climate change impact, adaptation, and vulnerability assessments offer a specific platform for exploring long-term future scenarios in which climate change is considered along with other projected changes of relevance to long-term planning.

In many situations, climate change may lead to non-marginal and irreversible outcomes, which pose challenges to conventional tools of economic and environmental policy. In addition, the realization that future climate may differ significantly from previous experience is still relatively new for many fields of practice (e.g., food production, natural resources management, natural hazards management, insurance, public health services, and urban planning).

Capacity barriers have hampered the transition from planning to implementation, so only a small number of jurisdictions have been successful at implementing adaptation measures (Section 15.2). However, there has been growth in community-based adaptation initiatives (Baer and Risbey, 2009; Rudiak-Gould, 2011; Sections 15.1, 15.2, 15.5, 15.6).

Various enabling factors for implementation have been identified in stakeholder engagement processes. Such factors include access to resources and sharing observations, language specific information, and ICT tools (e.g., wireless sensor networks, geographic information systems and web-based tools) that increase local awareness, allowing for good public understanding of stresses, risks, and trade-offs (Section 15.4.2). These factors allow new strategies to be explored, evaluated, and implemented (Shepherd et al., 2006; Hewitt et al., 2013). Enabling factors also include customized impact and vulnerability assessments for communities of interest and local practitioners who would serve as champions for adaptation planning, and the existence of local social influences/networks and capacity that enable long-term strategic planning and mainstreaming (Gardner et al., 2009; Cohen, 2010). These factors are further discussed in Chapters 15 and 16. Local government officials often lack training on climate change adaptation and require capacity to be built in a number of areas. To assist this process, guidebooks have been produced, framing the process of adaptation planning as both a team-building and project management exercise, activities that are already part of usual practice (Snover et al., 2007; Bizikova et al., 2008; ICLEI Oceania, 2008; CARE International in Vietnam, 2009; Ayers et al., 2012). Practitioner engagement in decision "games" can offer another training resource (Black et al., 2012).

2.5. Linking Adaptation with Mitigation and Sustainable Development

2.5.1. Assessing Synergies and Trade-offs with Mitigation

Capacities to adapt to and mitigate climate change are broadly similar. Opportunities for synergies are particularly relevant for the agriculture, forestry, urban infrastructure, energy, and water sectors (Chapters 3, 4, 7 to 10). The IPCC AR4 (Klein et al., 2007) concluded that a lack of information made it difficult to assess these synergies. Assessing the synergies and trade-offs that face both adaptation and mitigation is an important goal of the new IPCC scenario process (Kriegler et al., 2012; O'Neill et al., 2014). These synergies and trade-offs between adaptation and mitigation are illustrated in Figure 2-4. The negatives associated with "adaptive emissions" or "new vulnerabilities" arising from mitigation do not necessarily mean that such measures should not be contemplated, but they do need to be assessed within a larger portfolio of actions where losses and gains have been sufficiently well quantified (Section 19.7). Limits of adaptation emphasize the different reach of adaptation and mitigation in managing climate risks (Sections 16.6, 19.7.5).

Mitigation can affect, for example, water resources (Section 3.7.2.1), terrestrial and freshwater ecosystems (Sections 4.4.4, 19.3.2.2), agriculture (Sections 19.3.2.2, 19.4.1), and livelihoods and poverty (Section 13.3.1), and will in turn be affected by changes in water resources (Section 3.7.3.2) and terrestrial ecosystems (Sections 4.3.3.1, 4.2.4.1). Adaptation actions for agriculture generally tend to reduce emissions (Section 7.5.1.4). Potential losses of human security associated with climate policy are discussed in Sections 12.5.2 and 19.4.2.2. Recent literature on potential interactions between mitigation and adaptation is reviewed in Sections 16.4.3, 19.7.1, 19.7.2, 19.7.3, 19.7.4, and 19.7.5. Chapter 20 discusses the relationship between adaptation, mitigation, and sustainable development including sustainable risk management (Section 20.3.3).

2.5.2. Linkage with Sustainable Development: Resilience

The idea that climate change response and sustainable development should be integrated within a more holistic decision framework was assessed in IPCC AR4 (Robinson et al., 2006; Klein et al., 2007; Yohe et al., 2007). Practical aspects of this integration are being tested as decision makers endeavor to incorporate adaptation measures within official long-term development plans (Section 15.3.3). A typical example

is the engagement of researchers and practitioners (planners, engineers, water managers, etc.) in scenario-based exercises to build local capacity to plan for a wide range of climate outcomes (Bizikova et al., 2010). Development can yield adaptation co-benefits if climate change is factored into its design (Sections 17.2.7.2, 20.3, 20.4).

Resilience is the capacity to change in order to maintain the same identity (see Glossary) and can be assessed through participatory research (Tyler and Moench, 2012) or through system modelling. Chapter 20 examines climate-resilient pathways, which are development trajectories of combined mitigation and adaptation to realize the goal of sustainable development while meeting the goals of the UNFCCC (Box 20-1). An example of resilience assessment at the landscape scale is in the Arctic, where local sources of important productivity and biodiversity are being mapped and their future capacity in supporting larger ecoregions under climate change is being assessed (Christie and Sommerkorn, 2012). An industry example covers the resilience analysis of supply chains, specifically petrochemical supply chains exposed to a hurricane in the southeastern USA (Vugrin et al., 2011). For urban areas, Leichenko (2011) categorize four types of urban resilience studies: (1) urban ecological resilience, (2) urban hazards and disaster risk reduction, (3) resilience of urban and regional economies, and (4) urban governance and institutions. Boyd et al. (2008) promote resilience as a way of guiding future urbanization that would be better "climatized." The Asian Cities Climate Change Resilience Network is applying a resilience planning framework, with attention given to the role of agents and institutions (Tyler and Moench, 2012).

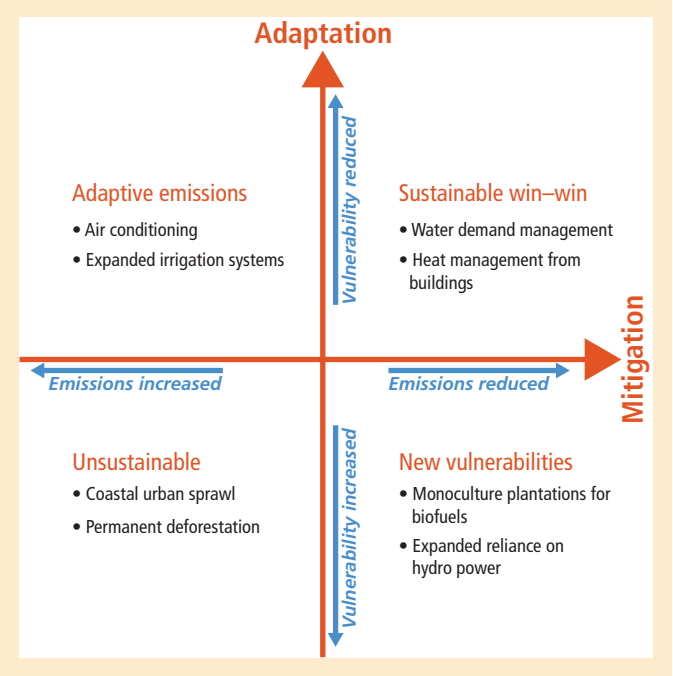


Figure 2-4 | Examples of adaptation (A): mitigation (M) trade-offs and synergies (adapted from Cohen and Waddell, 2009). The upper right quadrant (sustainable win–win) illustrates synergies in which actions enable the achievement of both adaptation and mitigation goals. The lower left quadrant (unsustainable) shows the opposite condition. The upper left (adaptive emissions) and lower right (new vulnerabilities) quadrants illustrate trade-offs that can result from actions within particular local-regional circumstances.

Adaptive capacity is seen as an important component of resilience on a range of scales (Sections 2.1.1, 2.2.3, 2.3.4, 2.4.2, 20.3). Local cases, such as King County (Seattle) USA, illustrate the importance of researcher-practitioner collaboration for knowledge exchange (Snover et al., 2007) and iterative and reflexive processes that enable local ownership, and adjustment to new information and evaluation of actions taken (Saavedra and Budd, 2009). However, in regions with high and chronic poverty, coupled with low awareness of global change drivers, adaptation as a process is not well understood and tools that enable anticipatory learning are lacking (Tschakert and Dietrich, 2010).

The normative concept of sustainable adaptation has been proposed to manage adaptation's unintended consequences (Eriksen et al., 2011). It considers effects on social justice and environmental integrity, challenging current (unsustainable) development paths rather than seeking adjustments within them. This concept recognizes the role of multiple stressors in vulnerability, the importance of values in affecting adaptation outcomes (Section 2.2.1), and potential feedbacks between local and global processes. Little is known about the long-term effects of adaptation on livelihoods and poverty (Section 13.3.2) although focusing on poverty alleviation as part of adaptation is thought to build capacity (Sections 13.4.1, 13.4.2).

The Hyogo Framework for Action on disaster risk reduction considers climate change as an underlying risk factor, and promotes the integration of risk reduction and climate change adaptation (UNISDR, 2007, 2011; see also Section 15.3.2). Social development is being integrated with disaster risk management in order to enhance adaptive capacity and address the structural causes of poverty, vulnerability, and exposure. In small island states, this integration is being enabled through focused institutional coordination, greater stakeholder engagement, and promotion of community-based adaptation and resilience-building projects (UNISDR and UNDP, 2012). Similar initiatives are underway in urban areas (UNISDR, 2012; see also Sections 15.3.2, 15.3.3, 15.5; Chapter 24; Box CC-TC).

Resilience is also being explored as an outcome of social contracts that underpin governance. O'Brien et al. (2009) use examples from Norway, New Zealand, and Canada to illustrate how resilience thinking on climate does not easily fit into existing social contracts, and that new types of arrangements may better serve the goals of resilience and sustainable development within the context of climate change. Chapter 20 describes climate-resilient development pathways as being an explicit objective of long-term planning and decision making and considers the need for transformational adaptation aiming to achieve sustainable development (Sections 20.5).

2.5.3. Transformation: How Do We Make Decisions Involving Transformation?

Much of the existing adaptation literature examines gradual adjustment or accommodation to change. But a growing literature highlights the importance of transformative adaptation (Sections 14.3.5, 16.4.2), both in the context of a world where global temperature raise above 2°C (Kates et al., 2012; PIK, 2012) and in the context of climate-resilient

pathways that manage risk through combinations of adaptation and mitigation (Section 20.5).

In concluding this chapter, we therefore reflect on some emerging, though still sparse, literature that examines such transformational adaptation, how it differs from incremental adaptation (O'Brien, 2012; Park et al., 2012), and how it might occur in specific sectors and systems (Rickards and Howden, 2012). This early literature suggests that many themes raised in this chapter may prove important to transformational adaptation, including iterative risk management with a broad view of risk, adaptive management, robustness and resilience, and deliberation (McGray et al., 2007; Leary et al., 2008; Hallegatte, 2009; Tschakert and Dietrich, 2010; Hallegatte et al., 2011; Stafford Smith et al., 2011). For instance, Irvin and Stansbury (2004) identify situations where participatory processes may be most effective for bringing about positive social and environmental change. Recently, Park et al. (2012) have proposed the Adaptation Action Cycles concept as a means to delineate incremental and transformative adaptation and the role of learning in the decision-making process. Similar to the learning process called "triple-loop"—which considers a situation, its drivers, plus the underlying frames and values that provide the situation context (Argyris and Schön, 1978; Peschl, 2007; Hargrove, 2008)—transformational adaptation may involve decision makers questioning deep underlying principles (Flood and Romm, 1996; Pelling et al., 2008) and seeking changes in institutions, such as legal and regulatory structures underlying environmental and natural resource management (Craig, 2010 ; Ruhl, 2010a), as well as in cultural values (O'Brien, 2012; O'Brien et al., 2013).

References

Abel, N., R. Gorddard, B. Harman, A. Leitch, J. Langridge, A. Ryan, and S. Heyenga, 2011: Sea level rise, coastal development and planned retreat: analytical framework, governance principles and an Australian case study. *Environmental Science & Policy*, **14**, 279-288.

Adger, W.N., 2003: Social capital, collective action, and adaptation to climate change. *Economic Geography*, **79**, 387-404.

Adger, W.N., 2006: Vulnerability. *Global Environmental Change*, **16**, 268-281.

Adger, W.N. and J. Barnett, 2009: Four reasons for concern about adaptation to climate change. *Environment and Planning A*, **41**, 2800-2805.

Adger, W.N., S. Agrawala, M. Mirza, C. Conde, K. O'Brien, J. Pulhin, R. Pulwarty, B. Smit, and K. Takahashi, 2007: Assessment of adaptation practices, options, constraints and capacity. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 717-743.

Adger, W.N., S. Dessai, M. Goulden, M. Hulme, I. Lorenzoni, D. Nelson, L. Naess, J. Wolf, and A. Wreford, 2009: Are there social limits to adaptation to climate change? *Climatic Change*, **93**, 335-354.

Adger, W.N., J. Barnett, K. Brown, N. Marshall, and K. O'Brien, 2013: Cultural dimensions of climate change impacts and adaptation. *Nature Climate Change*, **3**, 112-117.

Agarwal, A., 2010: Local institutions in adaptation to climate change. In: *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World* [Mearns, R. and A. Norton (eds.)]. The International Bank for Reconstruction and Development / The World Bank, Washington DC, USA, pp. 173-197.

Agrawala, S. and S. Fankhauser (eds.), 2008: *Economic Aspects of Adaptation to Climate Change: Costs, Benefits and Policy Instruments*. The Organisation for Economic Co-operation and Development (OECD) Publishing, Paris, France, 133 pp.

Alcamo, J., J.M. Moreno, B. Nováky, M. Bindi, R. Corobov, R.J.N. Devoy, C. Giannakopoulos, E. Martin, J.E. Olesen, and A. Shvidenko, 2007: Europe. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 541-580.

Althaus, C.E., 2005: A disciplinary perspective on the epistemological status of risk. *Risk Analysis*, **25**, 567-588.

Anderson, N.B., 2011: Special issue: psychology and global climate change. *American Psychologist*, **66(4)**, 241-328.

Andersson, B. and A. Wallin, 2000: Students' understanding of the greenhouse effect, the societal consequences of reducing CO_2 emissions and the problem of ozone layer depletion. *Journal of Research in Science Teaching*, **37**, 1096-1111.

André, K., L. Simonsson, Å.G. Swartling, and B.-O. Linnér, 2012: Method development for identifying and analysing stakeholders in climate change adaptation processes. *Journal of Environmental Policy & Planning*, **14**, 243-261.

Argyris, C. and D.A. Schön, 1978: *Organizational Learning: A Theory of Action Perspective*. Addison-Wesley, Reading, MA, USA, 356 pp.

Arnell, N.W., M.J.L. Livermore, S. Kovats, P.E. Levy, R. Nicholls, M.L. Parry, and S.R. Gaffin, 2004: Climate and socio-economic scenarios for global-scale climate change impacts assessments: characterising the SRES storylines. *Global Environmental Change: Human and Policy Dimensions*, **14**, 3-20.

Arnold, D.G. (ed.), 2011: *The Ethics of Global Climate Change*. Cambridge University Press, New York, NY, USA, 340 pp.

Asseng, S., F. Ewert, C. Rosenzweig, J. Jones, J. Hatfield, A. Ruane, K. Boote, P. Thorburn, R. Rötter, and D. Cammarano, 2013: Uncertainty in simulating wheat yields under climate change. *Nature Climate Change*, **3**, 827-832.

Atran, S., D.L. Medin, and N.O. Ross, 2005: The cultural mind: environmental decision making and cultural modeling within and across populations. *Psychological Review*, **112(4)**, 744-776.

Australian Public Service Commission, 2007: *Tackling Wicked Problems: A Public Policy Perspective*. Australian Public Service Commission, Canberra, ACT, Australia, 38 pp.

Ayers, J., S. Anderson, S. Pradhan, and T. Rossing, 2012: *Participatory Monitoring, Evaluation, Reflection and Learning for Community-based Adaptation: A Manual for Local Practitioners*. PMERL Manual, CARE International, London, UK, 87 pp.

Backus, G.A., T.S. Lowry, and D.E. Warren, 2013: The near-term risk of climate uncertainty among the U.S. states. *Climatic Change*, **116**, 495-522.

Badke-Schaub, P. and S. Strohschneider, 1998: Complex problem solving in the cultural context. *Le Travail Humain*, **61**, 1-28.

Baer, P. and J.S. Risbey, 2009: Uncertainty and assessment of the issues posed by urgent climate change. An editorial comment. *Climatic Change*, **92**, 31-36.

Barnett, J. and W. Adger, 2003: Climate dangers and atoll countries. *Climatic Change*, **61**, 321-337.

Barnett, J. and S. O'Neill, 2010: Maladaptation. *Global Environmental Change*, **20**, 211-213.

Baron, J. and M. Spranca, 1997: Protected values. *Organizational Behavior and Human Decision Processes*, **70,** 1-16.

Baron, J.S., L. Gunderson, C.D. Allen, E. Fleishman, D. McKenzie, L.A. Meyerson, J. Oropeza, and N. Stephenson, 2009: Options for national parks and reserves for adapting to climate change. *Environmental Management*, **44**, 1033-1042.

Bartley, T., 2007: How foundations shape social movements: the construction of an organizational field and the rise of forest certification. *Social Problems*, **54**, 229-255.

Bateman, B. and R. Rancier (eds.), 2012: *Case Studies in Integrated Water Resources Management: From Local Stewardship to National Vision*. American Water Resources Association, Middleburg, VA, USA, 60 pp.

Batie, S.S., 2008: Wicked problems and applied economics. *American Journal of Agricultural Economics*, **90**, 1176-1191.

Beck, U.,1992: *Risk Society: Towards a New Modernity*. Sage Publications, London, UK, 260 pp.

Beck, U., 2000: Risk society revisited: theory, politics and research programmes. In: *The Risk Society and Beyond: Critical Issues for Social Theory* [Adam, B., U. Beck, and J. van Loon (eds.)]. Sage Publications, London, UK, pp. 211-229.

Beck, U., 2010: Climate for change, or how to create a green modernity? *Theory, Culture & Society*, **27**, 254-266.

Bedsworth, L. and E. Hanak, 2012: Preparing California for a changing climate. *Climatic Change*, **111**, 1-4.

Bell, R.L. and N.G. Lederman, 2003: Understandings of the nature of science and decision making on science and technology based issues. *Science Education*, **87**, 352-377.

Berkhout, F., B. van den Hurk, J. Bessembinder, J. de Boer, B. Bregman, and M. van Drunen, 2013: Framing climate uncertainty: socio-economic and climate scenarios in vulnerability and adaptation assessments. *Regional Environmental Change*, 15 pp. (in press), link.springer.com/article/10.1007/s10113-013-0519-2.

Berman, R., C. Quinn, and J. Paavola, 2012: The role of institutions in the transformation of coping capacity to sustainable adaptive capacity. *Environmental Development*, **2**, 86-100.

Berrang-Ford, L., J.D. Ford, and J. Paterson, 2011: Are we adapting to climate change? *Global Environmental Change*, **21**, 25-33.

Bierbaum, R., J.B. Smith, A. Lee, M. Blair, L. Carter, F.S. Chapin III, P. Fleming, S. Ruffo, M. Stults, and S. McNeeley, 2013: A comprehensive review of climate adaptation in the United States: more than before, but less than needed. *Mitigation and Adaptation Strategies for Global Change*, **18**, 361-406.

Biesbroek, G.R., R.J. Swart, T.R. Carter, C. Cowan, T. Henrichs, H. Mela, M.D. Morecroft, and D. Rey, 2010: Europe adapts to climate change: comparing national adaptation strategies. *Global Environmental Change*, **20**, 440-450.

Biesbroek, G.R., J.E. Klostermann, C.J. Termeer, and P. Kabat, 2013: On the nature of barriers to climate change adaptation. *Regional Environmental Change*, **13**, 1119-1129.

Bizikova, L., T. Neale, and I. Burton, 2008: *Canadian Communities' Guidebook for Adaptation to Climate Change: Including an Approach to Generate Mitigation Co-Benefits in the Context of Sustainable Development*. 1st edn., Adaptation and Impacts Research Division, Environment Canada, and University of British Columbia, Vancouver, Canada, 97 pp.

Bizikova, L., S. Burch, S. Cohen, and J. Robinson, 2010: Linking sustainable development with climate change adaptation and mitigation. In: *Climate Change, Ethics and Human Security* [O'Brien, K., A.L.S. Clair, and B. Kristoffersen (eds.)]. Cambridge University Press, Cambridge, UK, pp. 157-179.

Black, C., J. Brislawn, G. Deheza, T. Finnessey, and C. McNutt, 2012: *Summary Report: Colorado Drought Tournament.* Report from September 2012 Drought Tournament, National Oceanic and Atmospheric Administration (NOAA), Boulder, CO, USA, 15 pp.

Böhm, G. and H.-R. Pfister, 2000: Action tendencies and characteristics of environmental risks. *Acta Psychologica*, **104**, 317-337.

Boyd, E., H. Osbahr, P.J. Ericksen, E.L. Tompkins, M.C. Lemos, and F. Miller, 2008: Resilience and 'climatizing' development: examples and policy implications. *Development*, **51**, 390-396.

Boyes, E., M. Stanisstreet, and V.S. Papantoniou, 1999: The ideas of Greek high school students about the "ozone layer". *Science Education*, **83**, 724-737.

Boykoff, M.T. and J.M. Boykoff, 2007: Climate change and journalistic norms: a case-study of US mass-media coverage. *Geoforum*, **38**, 1190-1204.

Bradbury, J.A., 2006: Risk communication in environmental restoration programs. *Risk Analysis*, **14**, 357-363.

Brander, K., 2010: Impacts of climate change on fisheries. *Journal of Marine Systems*, **79**, 389-402.

Bravo, M.T., 2009: Voices from the sea ice: the reception of climate impact narratives. *Journal of Historical Geography*, **35**, 256-278.

Brewer, P.R. and A. Pease, 2008: Federal climate politics in the United States: polarization and paralysis. In: *Turning Down the Heat: The Politics of Climate Policy in Affluent Democracies* [Compston, H. and I. Bailey (eds.)]. Palgrave Macmillan, New York, NY, USA, pp. 85-103.

Britton, N.R., 1986: Developing an understanding of disaster. *Journal of Sociology*, **22**, 254-271.

Broome, J., 2008: The ethics of climate change: pay now or pay more later? *Scientific American*, **298**, 96-102.

Brown, C., W. Werick, W. Leger, and D. Fay, 2011: A decision analytic approach to managing climate risks – application to the upper Great Lakes. *Journal of the American Water Resources Association*, **47**, 524-534.

Brown, D.A., 2012: *Climate Change Ethics: Navigating the Perfect Moral Storm*. Taylor and Francis, London, UK, 288 pp.

Brugnach, M., A. Dewulf, C. Pahl-Wostl, and T. Taillieu, 2008: Toward a relational concept of uncertainty: about knowing too little, knowing too differently, and accepting not to know. *Ecology and Society*, **13(2),** 30, www.ecologyand society.org/vol13/iss2/art30/.

Budescu, D.V., H.-H. Por, and S.B. Broomell, 2012: Effective communication of uncertainty in the IPCC reports. *Climatic Change*, **113**, 181-200.

Burch, S. and J. Robinson, 2007: A framework for explaining the links between capacity and action in response to global climate change. *Climate Policy*, **7**, 304-316.

Burch, S., S.R.J. Sheppard, A. Shaw, and D. Flanders, 2010: Planning for climate change in a flood-prone community: municipal barriers to policy action and the use of visualizations as decision-support tools. *Journal of Flood Risk Management*, **3**, 126-139.

Burley, J., R.J. McAllister, K. Collins, and C. Lovelock, 2012: Integration, synthesis and climate change adaptation: a narrative based on coastal wetlands at the regional scale. *Regional Environmental Change*, **12**, 581-593.

Burton, I. and E. May, 2004: The adaptation deficit in water resources management. *IDS Bulletin*, **35**, 31-37.

Caney, S., 2006: Cosmopolitan justice, rights and global climate change. *Canadian Journal of Law and Jurisprudence*, **19**, 255-278.

Caney, S., 2009: Climate change and the future: discounting for time, wealth, and risk. *Journal of Social Philosophy*, **40**, 163-186.

Cardona, O.D., M.K. van Aalst, J. Birkmann, M. Fordham, G. McGregor, R. Perez, R.S. Pulwarty, E.L.F. Schipper, and B.T. Sinh, 2012: Determinants of risk: exposure and vulnerability. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 65-108.

CARE International in Vietnam, 2009: *Mainstreaming Climate Change Adaptation: A Practitioner's Handbook*. CARE International in Vietnam, Ha Noi, Vietnam, 59 pp.

Carpenter, S.R., P.L. Pingali, E.M. Bennet, and M.B. Zurek (eds.), 2005: *Ecosystems and Human Well-being: Scenarios*. Vol. 2, Island Press, Washington, DC, USA, 596 pp.

Carter, T.R., M.L. Parry, H. Harasawa, and S. Nishioka, 1994: *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations*. Department of Geography, University College, London, UK and Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Japan, 59 pp.

Carter, T.R., R.N. Jones, X. Lu, S. Bhadwal, C. Conde, L.O. Mearns, B.C. O'Neill, M.D.A. Rounsevell and M.B. Zurek, 2007: New Assessment Methods and the Characterisation of Future Conditions. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.)] Cambridge University Press, Cambridge, UK, 133-171.

Carvalho, A. and J. Burgess, 2005: Cultural circuits of climate change in U.K. Broadsheet Newspapers, 1985–2003. *Risk Analysis*, **25(6)**, 1457-1469.

Cash, D.W., W.C. Clark, F. Alcock, N.M. Dickson, N. Eckley, D.H. Guston, J. Jaeger, and R.B. Mitchell, 2003: Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences of the United States of America*, **100**, 8086-8091.

Changnon, S.A., P.J. Lamb, and K.G. Hubbard, 1990: Regional climate centers: new institutions for climate services and climate-impact research. *Bulletin of the American Meteorological Society*, **71**, 527-537.

Christie, P. and M. Sommerkorn, 2012: *RACER: Rapid Assessment of Circum-Arctic Ecosystem Resilience*, 2nd edn., WWF Global Arctic Programme, Ottawa, Canada, 72 pp.

Christoplos, I., J. Mitchell, and A. Liljelund, 2001: Re-framing risk: the changing context of disaster mitigation and preparedness. *Disasters*, **25**, 185-198.

Ciscar, J.-C., A. Iglesias, L. Feyen, L. Szabó, D. Van Regemorter, B. Amelung, R. Nicholls, P. Watkiss, O.B. Christensen, and R. Dankers, 2011: Physical and economic consequences of climate change in Europe. *Proceedings of the National Academy of Sciences of the United States of America*, **108**, 2678-2683.

Cismaru, M., R. Cismaru, T. Ono, and K. Nelson, 2011: "Act on climate change": an application of protection motivation theory. *Social Marketing Quarterly*, **17**, 62-84.

Climate Change Science Program, 2009: *Best Practice Approaches for Characterizing, Communicating and Incorporating Scientific Uncertainty in Climate Decision Making* [Morgan, M. (Lead Author), H. Dowlatabadi, M. Henrion, D. Keith, R. Lempert, S. McBride, M. Small, and T. Wilbanks (Contributing Authors)]. Synthesis and Assessment Product 5.2, Report by the Climate Change Science Program (CCSP) and the Subcommittee on Global Change Research, National Oceanic and Atmospheric Administration, Washington, DC, USA, 96 pp.

Coastal Protection and Restoration Authority, 2007: *Louisiana's Comprehensive Master Plan for a Sustainable Coast*. Coastal Protection and Restoration Authority of Louisiana, Baton Rouge, LA, USA, 113 pp.

Cohen, S.J., 2010: From observer to extension agent – using research experiences to enable proactive response to climate change. *Climatic Change*, **100**, 131-136.

Cohen, S.J., 2011: Overview: climate change adaptation in rural and resource-dependent communities. In: *Climate Change Adaptation in Developed Nations* [Ford, J.D. and L. Berrang-Ford (eds.)]. Vol. 42, Springer, Dordrecht, Netherlands and New York, NY, USA, pp. 401-412.

Committee on New Orleans Regional Hurricane Protection Projects, 2009: *The New Orleans Hurricane Protection System*. The National Academies Press, Washington, DC, USA, 46 pp.

Cork, S., R.N. Jones, C. Butler, D. Cocks, I. Dunlop, and P. Howe, 2012: Towards scenarios for a sustainable and equitable future Australia. In: *Negotiating our Future: Living Scenarios for Australia to 2050* [Raupach, M.R., A.J. McMichael, J.J. Finnigan, L. Manderson, and B.H. Walker (eds.)]. Vol. 1, Australian Academy of Science, Canberra, ACT, Australia, pp. 115-151.

Corraliza, J.A. and J. Berenguer, 2000: Environmental values, beliefs, and actions: a situational approach. *Environment and Behavior*, **32**, 832-848.

Craig, R., 2010: 'Stationarity is dead' – long live transformation: five principles for climate change adaptation law. *Harvard Environmental Law Review*, **34**, 9-75.

Crate, S.A., 2011: Climate and culture: anthropology in the era of contemporary climate change. *Annual Review of Anthropology*, **40**, 175-194.

Crate, S.A. and M. Nuttal, 2009: *Anthropology and Climate Change: From Encounters to Actions*. Left Coast Press, Walnut Creek, CA, USA, 416 pp.

Daniell, K., I. White, and D. Rollin, 2009: Ethics and participatory water planning. In: *Proceedings of H2009: 32nd Hydrology and Water Resources Symposium, 30 November-3 December 2009, Newcastle, Australia*. Engineers Australia, Barton, ACT, Australia, pp. 1476-1487.

Davidson, D.J. and M. Haan, 2011: Gender, political ideology, and climate change beliefs in an extractive industry community. *Population & Environment*, **34**, 217-234.

De Groot, J.I. and L. Steg, 2007: Value orientations and environmental beliefs in five countries: validity of an instrument to measure egoistic, altruistic and biospheric value orientations. *Journal of Cross-Cultural Psychology*, **38**, 318-332.

De Groot, J.I. and L. Steg, 2008: Value orientations to explain beliefs related to environmental significant ebehavior: how to measure egoistic, altruistic, and biospheric value orientations. *Environment and Behavior*, **40**, 330-354.

de la Vega-Leinert, A.C., D. Schröter, R. Leemans, U. Fritsch, and J. Pluimers, 2008: A stakeholder dialogue on European vulnerability. *Regional Environmental Change*, **8**, 109-124.

Debels, P., C. Szlafsztein, P. Aldunce, C. Neri, Y. Carvajal, M. Quintero-Angel, A. Celis, A. Bezanilla, and D. Martínez, 2009: IUPA: a tool for the evaluation of the general usefulness of practices for adaptation to climate change and variability. *Natural Hazards*, **50**, 211-233.

DeGaetano, A.T., T.J. Brown, S.D. Hilberg, K. Redmond, K. Robbins, P. Robinson, M. Shulski, and M. McGuirk, 2010: Toward regional climate services: the role of NOAA's regional climate centers. *Bulletin of the American Meteorological Society*, **91**, 1633-1644.

Demeritt, D., 2001: The construction of global warming and the politics of science. *Annals of the Association of American Geographers*, **91**, 307-337.

Demeritt, D., 2006: Science studies, climate change and the prospects for constructivist critique. *Economy and Society*, **35**, 453-479.

Descola, P., 2010: *Diversité des Natures, Diversité des Cultures*. Bayard, Paris, France, 88 pp.

DesJardins, J.R., 2013: *Environmental Ethics: An Introduction to Environmental Philosophy*. 5th edn., Wadsworth, Boston, MA, USA, 304 pp.

Dessai, S. and M. Hulme, 2007: Assessing the robustness of adaptation decisions to climate change uncertainties: a case study on water resources management in the East of England. *Global Environmental Change*, **17**, 59-72.

Dessai, S., M. Hulme, R.J. Lempert, and R. Pielke Jr, 2009: Climate prediction: a limit to adaptation? In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, W.N., I. Lorenzoni and K.L. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK, pp. 49-57.

Dewulf, A., M. Craps, R. Bouwen, T. Taillieu, and C. Pahl-Wostl, 2005: Integrated management of natural resources: dealing with ambiguous issues, multiple actors and diverging frames. *Water Science and Technology*, **52**, 115-124.

Dietz, T. and P.C. Stern (eds.), 2008: *Public Participation in Environmental Assessment and Decision Making*. National Academies Press, Washington, DC, USA, 307 pp.

Dovers, S., 2009: Normalizing adaptation. *Global Environmental Change*, **19**, 4-6.

Dube, O.P. and B.M. Sekhwela, 2008: Indigenous knowledge, institutions and practices for coping with variable climate in the Limpopo basin of Botswana. In: *Climate Change and Adaptation* [Leary, N., J. Adejuwon, V. Barros, I. Burton, J. Kulkarni, and R. Lasco (eds.)]. Earthscan, London, UK, pp. 71-99.

Duffy, S. and M. Verges, 2010: Forces of nature affect implicit connections with nature. *Environment and Behavior*, **42**, 723-739.

Dupuy, J.-P. and A. Grinbaum, 2005: Living with uncertainty: from the precautionary principle to the methodology of ongoing normative assessment. *Comptes Rendus Geosciences*, **337**, 457-474.

Duval, T.S. and J.P. Mulilis, 1999: A person-relative-to-event (PrE) approach to negative threat appeals and earthquake preparedness: a field study. *Journal of Applied Social Psychology*, **29**, 495-516.

Ebi, K.L. and J.C. Semenza, 2008: Community-based adaptation to the health impacts of climate change. *American Journal of Preventive Medicine*, **35**, 501-507.

Ebi, K.L., S. Hallegatte, T. Kram, N.W. Arnell, T.R. Carter, J. Edmonds, E. Kriegler, R. Mathur, B.C. O'Neill, K. Riahi, H. Winkler, D. Vuuren, and T. Zwickel, 2014: A new scenario framework for climate change research: background, process, and future directions. *Climatic Change*, **122**, 363-372, 10 pp., doi:10.1007/s10584-013-0912-3.

Edwards, P.N., 2010: *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming*. MIT Press, Cambridge, MA., USA, 518 pp.

Eiser, J.R., A. Bostrom, I. Burton, D.M. Johnston, J. McClure, D. Paton, J. van der Pligt, and M.P. White, 2012: Risk interpretation and action: a conceptual framework for responses to natural hazards. *International Journal of Disaster Risk Reduction*, **1**, 5-16.

Endfield, G., 2011: Reculturing and particularizing climate discourses: weather, identity, and the work of George Manley. *Osiris*, **26**, 142-162.

English, P.B., A.H. Sinclair, Z. Ross, H. Anderson, V. Boothe, C. Davis, K. Ebi, B. Kagey, K. Malecki, and R. Shultz, 2009: Environmental health indicators of climate change for the United States: findings from the State Environmental Health Indicator Collaborative. *Environmental Health Perspectives*, **117**, 1673-1681.

Eriksen, S., P. Aldunce, C.S. Bahinipati, R.D.A. Martins, J.I. Molefe, C. Nhemachena, K. O'Brien, F. Olorunfemi, J. Park, and L. Sygna, 2011: When not every response to climate change is a good one: identifying principles for sustainable adaptation. *Climate and Development*, **3**, 7-20.

European Environmental Agency, 2013: *Late Lessons from Early Warnings: Science, Precaution, Innovation*. EEA Report, No.1/2013, European Environmental Agency, Copenhagen, Denmark, 760 pp.

FAO, 2013: *Fisheries Glossary*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, www.fao.org/fi/glossary/ (accessed 28 Feb. 2013).

Farbotko, C. and H. Lazrus, 2012: The first climate refugees? Contesting global narratives of climate change in Tuvalu. *Global Environmental Change*, **22**, 382-390.

Feenstra, J.F., I. Burton, J.B. Smith, and R.S.J. Tol (eds.), 1998: *Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies*. Version 2.0, United Nations Environment Programme (UNEP), Nairobi, Kenya and Institute for Environmental Studies, Vrije Universiteit, Amsterdam, Netherlands, 464 pp.

Fillmore, C.J. and B.T. Atkins, 1992: Towards a frame-based organization of the lexicon: the semantics of RISK and its neighbors. In: *Frames, Fields, and Contrasts: New Essays in Semantics and Lexical Organization* [Lehrer, A. and E. Kittay (eds.)]. Lawrence Erlbaum, Mahwah, NJ, USA, pp. 75-102.

Fiorino, D.J., 1990: Citizen participation and environmental risk: a survey of institutional mechanisms. *Science, Technology & Human Values*, **15**, 226-243.

Fischbach, J.R., D.R. Johnson, D.S. Ortiz, B.P. Bryant, M. Hoover, and J. Ostwald, 2012: *Coastal Louisiana Risk Assessment Model*. RAND Gulf States Policy Institute, Santa Monica, CA, USA 118 pp.

Fischer, A. and K. Glenk 2011: One model fits all? – On the moderating role of emotional engagement and confusion in the elicitation of preferences for climate change adaptation policies. *Ecological Economics*, **70**, 1178-1188.

Fisher, B.S., N. Nakicenovic, K. Alfsen, J.C. Morlot, F. de la Chesnaye, J.-C. Hourcade, K. Jiang, M. Kainuma, E. La Rovere, A. Matysek, A. Rana, K. Riahi, R. Richels, S. Rose, D. van Vuuren, and R. Warren, 2007: Issues related to mitigation in the long term context. In: *Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Metz, B., O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 169-250.

Flood, R.L. and N.R.A. Romm, 1996: *Diversity Management: Triple Loop Learning*. John Wiley and Sons, Chichester, UK, 253 pp.

Folke, C., 2006: Resilience: The emergence of a perspective for social-ecological systems analyses. *Global Environmental Change*, **16**, 253-267.

Ford, J.D. and L. Berrang-Ford (eds.), 2011: *Climate Change Adaptation in Developed Nations: From Theory to Practice*. Springer, Dordrecht, Netherlands, 490 pp.

Freudenberg, W.R., R.B. Gramling, S.B. Laska, and K.T. Erikson, 2009: *Catastrophe in the Making: The Engineering of Katrina and the Disasters of Tomorrow*. Island Press/Shearwater Books, Washington, DC, USA, 209 pp.

Gagnon Thompson, S.C. and M.A. Barton, 1994: Ecocentric and anthropocentric attitudes toward the environment. *Journal of Environmental Psychology*, **14**, 149-157.

Gallopín, G.C., 2006: Linkages between vulnerability, resilience, and adaptive capacity. *Global Environmental Change*, **16**, 293-303.

Gardiner, S.M., 2004: Ethics and global climate change. *Ethics*, **114**, 555-600.

Gardiner, S.M., 2011: *A Perfect Moral Storm: The Ethical Tragedy of Climate Change*. Oxford University Press, Oxford, UK and New York, NY, USA, 512 pp.

Gardiner, S.M., S. Caney, D. Jamieson, and H. Shue (eds.), 2010: *Climate Ethics: Essential Readings*. Oxford University Press, Oxford, UK and New York, NY, USA, 368 pp.

Gardner, J., A.-M. Dowd, C. Mason, and P. Ashworth, 2009: *A Framework for Stakeholder Engagement on Climate Adaptation.* CSIRO Climate Adaptation Flagship Working Paper No. 3, Commonwealth Scientific and Industrial Organisation (CSIRO), Canberra, ACT, Australia, 32 pp.

Garvey, J., 2008: *The EPZ Ethics of Climate Change: Right and Wrong in a Warming World*. Bloomsbury Academic, London, UK, 186 pp.

Garvin, T., 2001: Analytical paradigms: the epistemological distances between scientists, policy makers, and the public. *Risk Analysis*, **21**, 443-456.

Giddens, A., 2000: *Runaway World: How Globalization is Reshaping our Lives*. Routledge, New York, NY, USA, 124 pp.

Giddens, A., 2009: *The Politics of Climate Change*. Polity Press, Cambridge, UK and Malden, MA, USA, 264 pp.

Gifford, R., 2008: Psychology's essential role in alleviating the impacts of climate change. *Canadian Psychology*, **49**, 273.

Gigerenzer, G. and D.G. Goldstein, 1996: Reasoning the fast and frugal way: models of bounded rationality. *Psychological Review*, **103**, 650-669.

Glantz, M.H. (ed.), 1988: *Societal Responses to Regional Climate Change. Forecasting by Analogy.* Westview Press, Boulder, CO, USA, 428 pp.

Goloubinoff, M., E. Katz, and A. Lammel (eds.), 1997: *Antropología del Clima en el Mundo Hispanoamericano*, Vols. I & II, Vols. 49 and 50 Colección Biblioteca Abya-Yala, Ediciones Abya-Yala, Quito, Ecuador, 602 pp.

Green, D. and G. Raygorodetsky, 2010: Indigenous knowledge of a changing climate. *Climatic Change*, **100**, 239-242.

Green, D. and K.R. Smith, 2002: The implications of graduation: why developing nations will never produce more greenhouse gases than developed countries. *Journal of Energy and Development*, **28**, 15-40.

Grothmann, T. and A. Patt, 2005: Adaptive capacity and human cognition: the process of individual adaptation to climate change. *Global Environmental Change: Human and Policy Dimensions*, **15**, 199-213.

Grothmann, T. and F. Reusswig, 2006: People at risk of flooding: why some residents take precautionary action while others do not. *Natural Hazards*, **38**, 101-120.

Grothmann, T., K. Grecksch, M. Winges and B. Siebenhüner, 2013: Assessing institutional capacities to adapt to climate change–integrating psychological dimensions in the Adaptive Capacity Wheel. *Natural Hazards and Earth System Sciences Discussions*, **1**, 793-828.

Groves, D.G., M. Davis, R. Wilkinson, and R. Lempert, 2008: Planning for climate change in the inland empire: Southern California. *Water Resources IMPACT*, **10**, 14-17.

Groves, D.G., C. Sharon, and D. Knopman, 2012: *Planning Tool to Support Louisiana's Decisionmaking on Coastal Protection and Restoration*. RAND Gulf States Policy Institute, Santa Monica, CA, USA 82 pp.

Grundmann, R. and N. Stehr, 2010: Climate change: what role for sociology? A response to Constance Lever-Tracy. *Current Sociology*, **58**, 897-910.

Gupta, J., K. Termeer, J. Klostermann, S. Meijerink, M. van den Brink, P. Jong, and S. Nooteboom, 2008: *Institutions for Climate Change: A Method to Assess the Inherent Characteristics of Institutions to Enable the Adaptive Capacity of Society*. Institute for Environmental Studies, Vrije Universiteit, Amsterdam, Netherlands, 19 pp.

Gupta, J., C. Termeer, J. Klostermann, S. Meijerink, M. van den Brink, P. Jong, S. Nooteboom, and E. Bergsma, 2010: The adaptive capacity wheel: a method to assess the inherent characteristics of institutions to enable the adaptive capacity of society. *Environmental Science & Policy*, **13**, 459-471.

Güss, C.D., M.T. Tuason, and C. Gerhard, 2010: Cross-national comparisons of complex problem-solving strategies in two microworlds. *Cognitive Science*, **34**, 489-520.

Guston, D.H., 2001: Boundary organizations in environmental policy and science: an introduction. *Science, Technology & Human Values*, **26**, 399-408.

Hagerman, S., H. Dowlatabadi, K. Chan, and T. Satterfield, 2010: Integrative propositions for adapting conservation policy to the impacts of climate change. *Global Environmental Change*, **20**, 351-362.

Haines, A., R.S. Kovats, D. Campbell-Lendrum, and C. Carvalan, 2006: Climate change and human health: impacts, vulnerability, and mitigation. *The Lancet*, **367**, 2101-2109.

Hallegatte, S., 2009: Strategies to adapt to an uncertain climate change. *Global Environmental Change*, **19(2)**, 240-247.

Hallegatte, S., F. Lecocq, and C. de Perthuis, 2011: *Designing Climate Change Adaptation Policies: An Economic Framework*. Policy Research Working Paper 5568, The World Bank, Washington, DC, USA, 39 pp.

Hamblyn, R., 2009: The whistleblower and the canary: rhetorical constructions of climate change. *Journal of Historical Geography*, **35**, 223-236.

Hamilton, C., S. Adolphs, and B. Nerlich, 2007: The meanings of 'risk': a view from corpus linguistics. *Discourse Society*, **18**, 163-181.

Hansson, S.O., 2004: Philosophical perspectives on risk. *Techné*, **8**, 10-35.

Hansson, S.O., 2010: Risk: objective or subjective, facts or values. *Journal of Risk Research*, **13**, 231-238.

Hardee, K. and C. Mutunga, 2010: Strengthening the link between climate change adaptation and national development plans: lessons from the case of population in National Adaptation Programmes of Action (NAPAs). *Mitigation and Adaptation Strategies for Global Change*, **15**, 113-126.

Harding, R., 2006: Ecologically sustainable development: origins, implementation and challenges. *Desalination*, **187**, 229-239.

Hardman, D., 2009: *Judgment and Decision Making: Psychological Perspectives*. John Wiley and Sons, Chichester, UK, 232 pp.

Hargrove, R., 2008: *Masterful Coaching*. 3rd edn., Wiley, New York, NY, USA, 432 pp.

Harma, K.J., M.S. Johnson, and S.J. Cohen, 2012: Future water supply and demand in the Okanagan Basin, British Columbia: a scenario-based analysis of multiple, interacting stessors. *Water Resources Management*, **26**, 667-689.

Harris, P.G., 2010: *World Ethics and Climate Change: From International to Global Justice*. Edinburgh University Press, Edinburgh, UK, 208 pp.

Harrison, P.A., I.P. Holman, G. Cojocaru, K. Kok, A. Kontogianni, M.J. Metzger, and M. Gramberger, 2013: Combining qualitative and quantitative understanding for exploring cross-sectoral climate change impacts, adaptation and vulnerability in Europe. *Regional Environmental Change*, **13**, 761-780.

Held, D., 2004: Democratic accountability and political effectiveness from a cosmopolitan perspective. *Government and Opposition*, **39**, 364-391.

Hellmuth, M.E., S. Mason, C. Vaughan, M. van Aalst, and R. Choularton, 2011: *A Better Climate for Disaster Risk Management*. International Research Institute for Climate and Society (IRI), Columbia University, New York, NY, USA,118 pp.

Hess, J.J., J.Z. McDowell, and G. Luber, 2012: Integrating climate change adaptation into public health practice: using adaptive management to increase adaptive capacity and build resilience. *Environmental Health Perspectives*, **120**, 171-179.

Hewitt, C., S. Mason, and D. Walland, 2012: The global framework for climate services. *Nature Climate Change*, **2**, 831-832.

Hewitt, C., C. Buontempo, and P. Newton, 2013: Using climate predictions to better serve society's needs. *Eos, Transactions, American Geophysical Union*, **94**, 105-107.

Hinkel, J., 2011: Indicators of vulnerability and adaptive capacity: towards a clarification of the science-policy interface. *Global Environmental Change*, **21**, 198-208.

Hofstede, G., 1980: *Culture's Consequences: International Differences in Work-related Values*. Sage Publications, Beverly Hills, CA, USA, 327 pp.

Hofstede, G., 2001: *Culture's Consequences: Comparing Values, Behaviors, Institutions and Organizations Across Nations*. SAGE Publications, Thousand Oaks, CA, USA, 596 pp.

Hofstede, G., G.J. Hofstede, and M. Minkov, 2010: *Cultures and Organizations: Software of the Mind*. McGraw-Hill, New York, NY, USA, 562 pp.

Holling, C.S., 1978: *Adaptive Environmental Assessment and Management*. John Wiley and Sons, Chichester, UK, 377 pp.

Holling, C.S., 1996: Surprise for science, resilience for ecosystems, and incentives for people. *Ecological Applications*, **6**, 733-735.

Holsten, A. and J.P. Kropp, 2012: An integrated and transferable climate change vulnerability assessment for regional application. *Natural Hazards*, **64**, 1977-1999.

Huber, T. and P. Pedersen, 1997: Meteorological knowledge and environmental ideas in traditional and modern societies: the case of Tibet. *Journal of the Royal Anthropological Institute*, **3**, 577-597.

Hulme, M., 2009: *Why We Disagree About Climate Change: Understanding Controversy, Inaction and Opportunity*. Cambridge University Press, Cambridge, UK and New York, NY, USA, 392 pp.

Hulme, M., 2011: Reducing the future to climate: a story of climate determinism and reductionism. *Osiris*, **26**, 245-266.

Hulme, M. and M. Mahony, 2010: Climate change: what do we know about the IPCC? *Progress in Physical Geography*, **34**, 705-718.

Hunt, A., 2008: Informing adaptation to climate change in the UK: some sectoral impact costs. *Integrated Assessment*, **8**, 41-71.

Huq, S. and H. Reid, 2004: Mainstreaming adaptation in development. *IDS Bulletin*, **35**, 15-21.

ICLEI Oceania, 2008: *Local Government Climate Change Adaptation Toolkit*. Government of Australia and International Council for Local Envrionment Initiatives (ICLEI) – Australia/New Zealand Limited, Melbourne, Australia, 61 pp.

Ignatow, G., 2006: Cultural models of nature and society. *Environment and Behaviour*, **38**, 441-461.

Ingold, T., 2011: *The Perception of the Environment: Essays in Livelihood, Dwelling and Skill*. Routlege, London, UK and New York, NY, USA, 465 pp.

IPCC, 2007a: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 976 pp.

IPCC, 2007b: *Climate Change 2007: Synthesis Report* [Core Writing Team, Pachauri, R.K and A. Reisinger (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp.

IRGC, 2010: *The Emergence of Risks: Contributing Factors*. International Risk Governance Council, Geneva, Switzerland, 59 pp.

Irvin, R.A. and J. Stansbury, 2004: Citizen participation in decision making: is it worth the effort? *Public Administration Review*, **64**, 55-65.

ISO, 2009: *ISO 31000:2009 Risk Management – Principles and Guidelines*. International Organization for Standardization (ISO), Geneva, Switzerland, 24 pp.

Ison, R., 2010: *Systems Practice: How to Act in a Climate Change World*. Springer, London, UK, 324 pp.

Jäger, J., D. Rothman, C. Anastasi, S. Kartha, and P. van Notten, 2008: Training module 6: scenario development and analysis. In: *GEO Resource Book: A Training Manual on Integrated Environmental Assessment and Reporting*. International Institute for Sustainable Development (IISD), Winnipeg, Canada, and United Nations Environment Programme (UNEP), Nairobi, Kenya, 40 pp.

Jamieson, D., 1992: Ethics, public policy, and global warming. *Science, Technology & Human Values*, **17**, 139-153.

Jamieson, D., 1996: Ethics and intentional climate change. *Climatic Change*, **33**, 323-336.

Jasanoff, S., 1996: Beyond epistemology: relativism and engagement in the politics of science. *Social Studies of Science*, **26**, 393-418.

Jasanoff, S., 2010: Testing time for climate science. *Science*, **328**, 695-696.

Jønch-Clausen, T., 2010: Application of integrated approaches in water resources management beyond the conceptual phase In: *A Review of Selected Hydrology Topics to Support Bank Operations* [García, L.E., G. Puz, and A. Mejia (eds.)]. The World Bank, Washington DC, USA, pp. 13-34.

Jones, R., 2010: A risk management approach to climate change adaptation. In: *Climate Change Adaptation in New Zealand: Future Scenarios and Some Sectoral Perspectives* [Nottage, R.A.C., D.S. Wratt, J.F. Bornman, and K. Jones (eds.)]. New Zealand Climate Change Centre, Wellington, New Zealand, pp. 10-25.

Jones, R., 2011: The latest iteration of IPCC uncertainty guidance – an author perspective. *Climatic Change*, **108**, 733-743.

Jones, R.G., M. Noguer, D.C. Hassell, D. Hudson, S.S. Wilson, G.J. Jenkins, and J.F.B. Mitchell, 2004: *Generating High Resolution Climate Change Scenarios Using PRECIS*. Met Office Hadley Centre, Exeter, UK, 40 pp.

Jones, R.N., 2001: An environmental risk assessment/management framework for climate change impact assessments. *Natural Hazards*, **23**, 197-230.

Jones, R.N., 2012: Applying scenarios to complex issues: Australia 2050. In: *Negotiating Our Future: Living Scenarios for Australia to 2050* [Raupach, M.R., T. McMichael, John J. Finnigan, L. Manderson, and B.H. Walker (eds.)]. Vol. 2, Australian Academy of Science, Canberra, ACT, Australia, pp. 173-190.

Jones, R.N. and B.L. Preston, 2011: Adaptation and risk management. *WIREs Climate Change*, **2**, 296-308.

Jones, R.N., C.K. Young, J. Handmer, A. Keating, G.D. Mekala, and P. Sheehan, 2013: *Valuing Adaptation Under Rapid Change*. National Climate Change Adaptation Research Facility, Gold Coast, Australia, 182 pp.

Jones, S.A., B. Fischhoff, and D. Lach, 1999: Evaluating the science-policy interface for climate change research. *Climatic Change*, **43**, 581-599.

Kahan, D.M. and D. Braman, 2006: Cultural cognition and public policy. *Yale Law and Policy Review*, **24**, 147-171.

Kahan, D.M., D. Braman, P. Slovic, J. Gastil, and G.L. Cohen, 2007: *The Second National Risk and Culture Study: Making Sense of – and Making Progress In – The American Culture War of Fact*. GWU Legal Studies Research Paper No. 370, Yale Law School Public Law Working Paper No. 154, GWU Law School Public Law Research Paper No. 370, Harvard Law School Program on Risk Regulation Research Paper No. 08-26, 20 pp., ssrn.com/abstract=1017189, doi:10.2139/ssrn.1017189.

Kahneman, D., 2011: *Thinking, Fast and Slow*. 1st edn., Farrar, Straus, and Giroux, New York, NY, USA, 499 pp.

Kahneman, D. and A. Tversky, 1979: Prospect theory: an analysis of decision under risk. *Econometrica*, **47**, 263-292.

Kambhu, J., S. Weidman, and N. Krishnan, 2007: *New Directions for Understanding Systemic Risk: A Report on a Conference Cosponsored by the Federal Reserve Bank of New York and the National Academy of Sciences*. National Academies Press, Washington, DC, USA, 90 pp.

Kandlikar, M., J. Risbey, and S. Dessai, 2005: Representing and communicating deep uncertainty in climate-change assessments. *Comptes Rendus Geoscience*, **337**, 443-455.

Kandlikar, M., H. Zerriffi, and C. Ho Lem, 2011: Science, decision-making and development: managing the risks of climate variation in less-industrialized countries. *Wiley Interdisciplinary Reviews: Climate Change*, **2**, 201-219.

Kasperson, R.E., 1992: The social amplification of risk: progress in developing an integrative framework in social theories of risk. In: *Social Theories of Risk* [Krimsky, S. and D. Golding (eds.)]. Praeger, Westport, CT, USA, pp. 53-178.

Kasperson, R.E., O. Renn, P. Slovic, H.S. Brown, J. Emel, R. Goble, J.X. Kasperson, and S. Ratick, 1988: The social amplification of risk: a conceptual framework. *Risk Analysis*, **8**, 177-187.

Kasprzyk, J.R., S. Nataraj, P.M. Reed, and R.J. Lempert, 2013: Many objective robust decision making for complex environmental systems undergoing change. *Environmental Modelling & Software*, **42**, 55-71.

Kates, R.W., W.R. Travis, and T.J. Wilbanks, 2012: Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences of the United States of America*, **109**, 7156-7161.

Katz, E., A. Lammel, and M. Goloubinoff (eds.), 2002: *Entre Ciel et Terre: Climat et Sociétés*. IRD Editions, Ibis Press, Paris, France, 509 pp.

Kazdin, A.E., 2009: Psychological science's contributions to a sustainable environment: extending our reach to a grand challenge of society. *American Psychologist*, **64**, 339.

Keeney, R.L., 1992: *Value-focused Thinking: A Path to Creative Decisionmaking*. Harvard University Press, Cambridge, MA., USA, 432 pp.

Keeney, R.L. and H. Raiffa, 1993: *Decisions with Multiple Objectives: Preferences and Value Trade-Offs*. Cambridge University Press, Cambridge, UK, 569 pp.

Kern, K. and G. Alber, 2008: Governing climate change in cities: modes of urban climate governance in multi-level systems. In: *Competitive Cities and Climate Change: OECD Conference Proceedings, Milan, Italy, 9-10 October 2008* [Elliott, V.C. (ed.)]. The Organisation for Economic Co-operation and Development (OECD), Paris, France, pp. 171-196.

Kindon, S., R. Pain, and M. Kesby, 2007: *Participatory Action Research Approaches and Methods: Connecting People, Participation and Place*. Routledge, Abingdon, UK and New York, NY, USA, 288 pp.

Kirchhoff, C.J., M.C. Lemos, and N.L. Engle, 2012: What influences climate information use in water management? The role of boundary organizations and governance regimes in Brazil and the US. *Environmental Science & Policy*, **26**, 6-18.

Klein, R.J.T., S. Huq, F. Denton, T.E. Downing, R.G. Richels, J.B. Robinson, and F.L. Toth, 2007: Inter-relationships between adaptation and mitigation. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working*

Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J.v.d. Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 745-777.

Klinke, A. and O. Renn, 2002: A new approach to risk evaluation and management: risk-based, precaution-based, and discourse-based strategies. *Risk Analysis*, **22**, 1071-1094.

Klöckner, C.A. and A. Blöbaum, 2010: A comprehensive action determination model: toward a broader understanding of ecological behaviour using the example of travel mode choice. *Journal of Environmental Psychology*, **30**, 574-586.

Kolk, A. and J. Pinkse, 2010: *The Climate Change – Development Nexus and Tripartite Partnerships*. The Partnerships Resource Centre Working Paper Series, Working Paper 006, The Partnerships Resource Centre, Rotterdam, Netherlands, 18 pp.

Korteling, B., S. Dessai, and Z. Kapelan, 2013: Using information-gap decision theory for water resources planning under severe uncertainty. *Water Resources Management*, **27**, 1149-1172.

Krauss, W., 2011: Rooted in society. *Nature Geoscience*, **3**, 513-514.

Krauss, W. and H. von Storch, 2012: Post-normal practices between regional climate services and local knowledge. *Nature and Culture*, **7**, 213-230.

Kriegler, E., B.C. O'Neill, S. Hallegatte, T. Kram, R.J. Lempert, R.H. Moss, and T. Wilbanks, 2012: The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathways. *Global Environmental Change*, **22**, 807-822.

Krupnik, I. and D. Jolly (eds.), 2002: *The Earth Is Faster Now: Indigenous Observations of Arctic Environmental Change.* Frontiers in Polar Social Science, Arctic Research Consortium of the United States, Fairbanks, AK, USA, 384 pp.

Kuik, O., B. Buchner, M. Catenacci, A. Goria, E. Karakaya, and R. Tol, 2008: Methodological aspects of recent climate change damage cost studies. *Integrated Assessment*, **8**, 19-40.

Kuruppu, N., 2009: Adapting water resources to climate change in Kiribati: the importance of cultural values and meanings. *Environmental Science & Policy*, **12**, 799-809.

Kwadijk, J.C., M. Haasnoot, J.P. Mulder, M. Hoogvliet, A. Jeuken, R.A. van der Krogt, N.G. van Oostrom, H.A. Schelfhout, E.H. van Velzen, and H. van Waveren, 2010: Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands. *Wiley Interdisciplinary Reviews: Climate Change*, **1**, 729-740.

Lal, P.N., T. Mitchell, P. Aldunce, H. Auld, R. Mechler, A. Miyan, L.E. Romano, and S. Zakaria, 2012: National systems for managing the risks from climate extremes and disasters. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 339-392.

Lammel, A. and T. Kozakai, 2005: Percepción y representación de los riesgos de la contaminación atmosférica según el pensamiento holístico y el pensamiento analítico. *Desacatos*, **19**, 85-98.

Lammel, A., M. Goloubinoff, and E. Katz, 2008: *Aires y Lluvias. Antropología del Clima en México*. Centro de Investigaciones y Estudios Superiores en Antropología Social (CIESAS) and Centro de Estudios Mexicanos y Centroamericanos (CEMCA), and Institut de Recherche pour le Developpement (IRD), Publicaciones de la casa chata, Mexico City, Mexico, 640 pp.

Lammel, A., C. Guillen, E. Dugas, and F. Jamet, 2010: Cultural and environmental changes: cognitive adaptation to global warming. In: *Steering the Cultural Dynamics: Selected Papers from the 2010 Congress of the International Association for Cross-Cultural Psychology* [Kashima, Y., E. Kashima, and R. Beatson (eds.)]. eBook, International Association for Cross-Cultural Psychology (IACCP), Melbourne, Australia, pp. 49-58, www.iaccp.org/drupal/sites/default/files/melbourne_pdf/Melbourne%20Proceedings.pdf.

Lammel, A., E. Dugas, and C. Guillen, 2011: Traditional way of thinking and prediction of climate change in New Caledonia (France). *Indian Journal of Traditional Knowledge*, **10**, 13-20.

Lammel, A., E. Dugas, and E. Guillen Gutierrez, 2012: L'apport de la psychologie cognitive à l'étude de l'adaptation aux changements climatiques: la notion de vulnérabilité cognitive. *VertigO – la revue électronique en sciences de l'environnement*, **12(1)**, doi:10.4000/vertigo.11915.

László, J. and B. Ehmann, 2012: Narrative social psychology. In*: Social Cognition and Communication* [Laszlo, J., J. Forgas, and O. Vincze (eds.)]. Vol. 15, Sydney Symposium of Social Psychology Series, Report from EASP Small Group Meeting on Social Cognition and Communication, 9 -12th July, 2012, Pecs, Hungary, Psychology Press (Taylor and Francis Group), New York, NY, USA, pp. 205-228.

Lateef, F., 2009: Cyclone Nargis and Myanmar: a wake up call. *Journal of Emergencies, Trauma and Shock*, **2**, 106-113.

Leary, N., J. Adejuwon, V. Barros, I. Burton, J. Kulkarni, and R. Lasco (eds.), 2008: *Climate Change and Adaptation*, Earthscan, London, UK, 381 pp.

Lebel, L., T. Grothmann, and B. Siebenhüner, 2010: The role of social learning in adaptiveness: insights from water management. *International Environmental Agreements: Politics, Law and Economics*, **10**, 333-353.

Leichenko, R., 2011: Climate change and urban resilience. *Current Opinion in Environmental Sustainability*, **3**, 164-168.

Leiserowitz, A., 2006: Climate change risk perception and policy preferences: the role of affect, imagery, and values. *Climatic Change*, **77**, 45-72.

Lempert, R.J, 2012: Scenarios that illuminate vulnerabilities and robust responses. *Climatic Change*, **117(4)**, 627-646.

Lempert, R.J. and M.T. Collins, 2007: Managing the risk of uncertain threshold responses: comparison of robust, optimum, and precautionary approaches. *Risk Analysis*, **27**, 1009-1026.

Lempert, R.J. and N. Kalra, 2011: *Managing Climate Risks in Developing Countries with Robust Decision Making*. World Resources Report Uncertainty Series, World Resources Institute, Washington, DC, USA, 9 pp.

Lempert, R.J. and S. McKay, 2011: Some thoughts on the role of robust control theory in climate-related decision support. *Climatic Change*, **107**, 241-246.

Lempert, R.J. and M.E. Schlesinger, 2002: Adaptive strategies for climate change. In: *Innovative Energy Strategies for CO_2 Stabilization* [Watts, R.G. (ed.)]. Cambridge University Press, New York, NY, USA, pp. 45-85.

Lempert, R.J., N. Nakicenovic, D. Sarewitz, and M. Schlesinger, 2004: Characterizing climate-change uncertainties for decision-makers: an editorial essay. *Climatic Change*, **65**, 1-9.

Lindell, M.K. and R.W. Perry, 2012: The protective action decision model: theoretical modifications and additional evidence. *Risk Analysis*, **32**, 616-632.

Llasat, M.C., M. Llasat-Botija, and L. López, 2009: A press database on natural risks and its application in the study of floods in Northeastern Spain. *Natural Hazards and Earth System Sciences*, **9**, 2049-2061.

Lobell, D.B., M.B. Burke, C. Tebaldi, M.D. Mastrandrea, W.P. Falcon, and R.L. Naylor, 2008: Prioritizing climate change adaptation needs for food security in 2030. *Science*, **319**, 607-610.

Lorenzoni, I., A. Leiserowitz, M.D.F. Doria, W. Poortinga, and N.F. Pidgeon, 2006: Cross-national comparisons of image associations with "global warming" and "climate change" among laypeople in the United States of America and Great Britain. *Journal of Risk Research*, **9**, 265-281.

Lundgren, R.E. and A.H. McMakin, 2013: *Risk Communication: A Handbook for Communicating Environmental, Safety, and Health Risks*. John Wiley & Sons, Hoboken, NJ, USA, 416 pp.

Macaulay, A.C., L.E. Commanda, W.L. Freeman, N. Gibson, M.L. McCabe, C.M. Robbins, and P.L. Twohig, 1999: Participatory research maximises community and lay involvement. *British Medical Journal*, **319**, 774-778.

Macintosh, A., A. Foerster, and J. McDonald, 2013: *Limp, Leap or Learn? Developing Legal Frameworks for Climate Change Adaptation Planning in Australia*. National Climate Change Adaptation Research Facility (NCCARF), Gold Coast, Australia, 277 pp.

Maddux, J.E. and R.W. Rogers, 1983: Protection motivation and self-efficacy: a revised theory of fear appeals and attitude change. *Journal of Experimental Social Psychology*, **19**, 469-479.

Madzwamuse, M., 2010: *Climate Governance in Africa – Adaptation Strategies and Institutions*. Heinrich Böll Stiftung, Cape Town, South Africa, 110 pp.

Magistro, J. and C. Roncoli, 2001: Anthropological perspectives and policy implications of climate change research. *Climate Research*, **19**, 91-96.

Mahony, M. and M. Hulme, 2012: Model migrations: mobility and boundary crossings in regional climate prediction. *Transactions of the Institute of British Geographers*, **37**, 197-211.

Martin, J., P. Fackler, J. Nichols, B. Lubow, M. Eaton, M. Runge, B. Stith, and C. Langtimm, 2011: Structured decision making as a proactive approach to dealing with sea level rise in Florida. *Climatic Change*, **107(1-2)**, 185-202.

Marx, S.M., E.U. Weber, B.S. Orlove, A. Leiserowitz, D.H. Krantz, C. Roncoli, and J. Phillips, 2007: Communication and mental processes: experiential and analytic processing of uncertain climate information. *Global Environmental Change*, **17**, 47-58.

Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Frame, H. Held, E. Kriegler, K.J. Mach, P.R. Matschoss, G.-K. Plattner, G.W. Yohe, and F.W. Zwiers, 2010: *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties*. Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, 6 pp.

McCray, L.E., K.A. Oye, and A.C. Petersen, 2010: Planned adaptation in risk regulation: an initial survey of US environmental, health, and safety regulation. *Technological Forecasting and Social Change*, **77**, 951-959.

McDonald, G. and M.B. Lane, 2004: Converging global indicators for sustainable forest management. *Forest Policy and Economics*, **6**, 63-70.

McEvoy, J. and M. Wilder, 2012: Discourse and desalination: potential impacts of proposed climate change adaptation interventions in the Arizona-Sonora border region. *Global Environmental Change*, **22**, 353-363.

McGray, H., A. Hammill, R. Bradley, E.L. Schipper, and J.-E. Parry, 2007: *Weathering the Storm: Options for Framing Adaptation and Development*. World Resources Institute, Washington, DC, USA, 57 pp.

McNie, E.C., 2007: Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature. *Environmental Science & Policy*, **10**, 17-38.

Meadowcroft, J., 2009: *Climate Change Governance*. Policy Research Working Paper 4941, The World Bank, Washington, DC, USA, 40 pp.

Measham, T., B. Preston, T. Smith, C. Brooke, R. Gorddard, G. Withycombe, and C. Morrison, 2011: Adapting to climate change through local municipal planning: barriers and challenges. *Mitigation and Adaptation Strategies for Global Change*, **18**, 889-909.

Meijnders, A.L., C.J. Midden, and H.A. Wilke, 2002: Role of negative emotion in communication about CO_2 risks. *Risk Analysis*, **21**, 955-955.

Mercer, J., I. Kelman, K. Lloyd, and S. Suchet-Pearson, 2008: Reflections on use of participatory research for disaster risk reduction. *Area*, **40**, 172-183.

Mercer, J., I. Kelman, S. Suchet-Pearson, and K. Lloyd, 2009: Integrating indigenous and scientific knowledge bases for disaster risk reduction in Papua New Guinea. *Geografiska Annaler: Series B, Human Geography*, **91**, 157-183.

Metzger, M.J. and D. Schröter, 2006: Towards a spatially explicit and quantitative vulnerability assessment of environmental change in Europe. *Regional Environmental Change*, **6**, 201-216.

Meuleman, L. and R.J. in 't Veld, 2010: Sustainable development and the governance of long-term decisions. In: *Knowledge Democracy: Consequences for Science, Politics, and Media* [in 't Veld, R.J. (ed.)]. Springer-Verlag Berlin Heidelberg, Germany, pp. 255-281.

Miles, E.L., A.K. Snover, L.C. Whitely Binder, E.S. Sarachik, P.W. Mote, and N. Mantua, 2006: An approach to designing a national climate service. *Proceedings of the National Academy of Sciences of the United States of America*, **103**, 19616-19623.

Milfont, T.L., 2012: The interplay between knowledge, perceived efficacy, and concern about global warming and climate change: a one-year longitudinal study. *Risk Analysis*, **32**, 1003-1020.

Milfont, T.L. and V.V. Gouveia, 2006: Time perspective and values: an exploratory study of their relations to environmental attitudes. *Journal of Environmental Psychology*, **26**, 72-82.

Milfont, T.L., C.G. Sibley, and J. Duckitt, 2010: Testing the moderating role of the components of norm activation on the relationship between values and environmental behavior. *Journal of Cross-Cultural Psychology*, **41**, 124-131.

Mills, E., 2005: Insurance in a climate of change. *Science*, **309**, 1040-1044.

Minteer, B.A. and J.P. Collins, 2005a: Ecological ethics: building a new tool kit for ecologists and biodiversity managers. *Conservation Biology*, **19**, 1803-1812.

Minteer, B.A. and J.P. Collins, 2005b: Why we need an "ecological ethics". *Frontiers in Ecology and the Environment*, **3**, 332-337.

Minteer, B.A. and J.P. Collins, 2010: Move it or lose it? The ecological ethics of relocating species under climate change. *Ecological Applications*, **20**, 1801-1804.

Mitchell, R.B., 2006: *Global Environmental Assessments*. MIT Press, Cambridge, MA, USA, 344 pp.

Monterroso, A., C. Conde, C. Gay, D. Gómez, and J. López, 2012: Two methods to assess vulnerability to climate change in the Mexican agricultural sector. *Mitigation and Adaptation Strategies for Global Change*, doi:10.1007/s11027-012-9442-y.

Montréal Process, 2009: *Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests.* The Montréal Process, 4th edn., Montreal Process Liaison Office, Tokyo, Japan, 29 pp.

Morgan, M.G., 2002: *Risk Communication: A Mental Models Approach*. Cambridge University Press, New York, NY, USA, 351 pp.

Morgan, M.G., M. Henrion, and M. Small, 1990: *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*. Cambridge University Press, Cambridge, UK and New York, NY, USA, 332 pp.

Moser, S., 2009: Making a difference on the ground: the challenge of demonstrating the effectiveness of decision support. *Climatic Change*, **95**, 11-21.

Moser, S.C. and J.A. Ekstrom, 2010: A framework to diagnose barriers to climate change adaptation. *Proceedings of the National Academy of Sciences of the United States of America*, **107**, 22026-22031.

Moss, R.H., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren, T.R. Carter, S. Emori, M. Kainuma, T. Kram, G.A. Meehl, J.F.B. Mitchell, N. Nakicenovic, K. Riahi, S.J. Smith, R.J. Stouffer, A.M. Thomson, J.P. Weyant, and T.J. Wilbanks, 2010: The next generation of scenarios for climate change research and assessment. *Nature*, **463**, 747-756.

Mulilis, J.P. and T.S. Duval, 1995: Negative threat appeals and earthquake preparedness: a person-relative-to-event (PrE) model of coping with threat. *Journal of Applied Social Psychology*, **25**, 1319-1339.

Munich Re Group, 2011: *Topics Geo: Natural Catastrophes 2010: Analyses, Assessments, Positions*. Münchener Rückversicherungs-Gesellschaft, Munich, Germany, 56 pp.

Murphy, J., D. Sexton, G. Jenkins, B. Booth, C. Brown, R. Clark, M. Collins, G. Harris, E. Kendon, and R. Betts, 2009: *UK Climate Projections Science Report: Climate Change Projections*. Met Office Hadley Centre, Exeter, UK, 192 pp.

Nakashima, D.J., G.K. Mclean, H.D. Thulstrup, R. Castillo, and J.T. Rubis, 2012: *Weathering Uncertainty: Traditional Knowledge for Climate Change Assessment and Adaptation*. United Nations Educational, Scientific, and Cultural Organization (UNESCO), Paris, France, and United Nations University (UNU), Darwin, Australia, 120 pp.

Nanda, V.P., 2012: *Climate Change and Environmental Ethics*. Transaction Publishers, New Brunswick, NJ, USA, 262 pp.

Narain, U., S. Margulis, and T. Essam, 2011: Estimating costs of adaptation to climate change. *Climate Policy*, **11**, 1001-1019.

National Research Council, 2001: *A Climate Services Vision: First Steps Toward the Future*. National Academic Press, Washington DC, USA, 84 pp.

National Research Council, 2007: *Research and Networks for Decision Support in the NOAA Sectoral Applications Research Program* [Ingram, H.M. and P.C. Stern (eds.)]. National Academies Press, Washington, DC, USA, 85 pp.

National Research Council, 2009a: *Informing Decisions in a Changing Climate*. National Academies Press, Washington DC, USA, 201 pp.

National Research Council, 2009b: *Science and Decisions: Advancing Risk Assessment*. National Academies Press, Washington, DC, USA, 424 pp.

National Research Council, 2011: *America's Climate Choices*. The National Academies Press, Washington DC, USA, 144 pp.

Nelson, D.R., W.N. Adger, and K. Brown, 2007: Adaptation to environmental change: contributions of a resilience framework. *Annual Review of Environment and Resources*, **32**, 395-419.

Nelson, J.A., 2011: The relational economy. In: *Ethical Principles and Economic Transformation – A Buddhist Approach* [Zsolnai, L. (ed.)]. Vol. 33, Springer, Dordrecht, Netherlands, pp. 21-33.

New, M., A. Lopez, S. Dessai, and R. Wilby, 2007: Challenges in using probabilistic climate change information for impact assessments: an example from the water sector. *Philosophical Transactions of the Royal Society A*, **365**, 2117-2131.

Nilsson, A., C. von Borgstede, and A. Biel, 2004: Willingness to accept climate change strategies: the effect of values and norms. *Journal of Environmental Psychology*, **24**, 267-277.

Nisbett, R.E. and Y. Miyamoto, 2005: The influence of culture: holistic versus analytic perception. *Trends in Cognitive Sciences*, **9**, 467-473.

Nisbett, R.E., K. Peng, I. Choi, and A. Norenzayan, 2001: Culture and system of thought: holistic versus analytic cognition. *Psychological Review*, **108**, 291-310.

Nordhaus, W.D., 2007: A review of the "Stern Review on the Economics of Climate Change". *Journal of Economic Literature*, **45**, 686-702.

North, D.C., 1990: *Institutions, Institutional Change and Economic Performance*. Cambridge University Press, New York, NY, USA, 152 pp.

Nyong, A., F. Adesina, and B. Osman Elasha, 2007: The value of indigenous knowledge in climate change mitigation and adaptation strategies in the African Sahel. *Mitigation and Adaptation Strategies for Global Change*, **12**, 787-797.

O'Brien, K., 2012: Global environmental change II: from adaptation to deliberate transformation. *Progress in Human Geography*, **36**, 667-676.

O'Brien, K., S. Eriksen, L.P. Nygaard, and A. Schjolden, 2007: Why different interpretations of vulnerability matter in climate change discourses. *Climate Policy*, **7**, 73-88.

O'Brien, K., B. Hayward, and F. Berkes, 2009: Rethinking social contracts: building resilience in a changing climate. *Ecology and Society*, **14(2)**, 12, www.ecologyandsociety.org/vol14/iss2/art12/.

O'Brien, K., A.L.S. Clair and B. Kristoffersen, (eds.), 2010: *Climate Change, Ethics And Human Security*, Cambridge University Press, Cambridge, UK, 231 pp.

O'Brien, K., J. Reams, A. Caspari, A. Dugmore, M. Faghihimani, I. Fazey, H. Hackmann, D. Manuel-Navarrete, J. Marks, R. Miller, K. Raivio, P. Romero-Lankao, H. Virji, C. Vogel and V. Winiwarter, 2013: You say you want a revolution? Transforming education and capacity building in response to global change. *Environmental Science & Policy*, **28**, 48-59.

O'Neill, B., E. Kriegler, K. Riahl, K. Ebi, S. Hallegatte, T. Carter, R. Mathur, and D. van Vuuren, 2013: A new scenario framework for climate change research: the concept of shared socio-economic pathways. *Climatic Change*, **122**, 387-400, doi:10.1007/s10584-013-0905-2.

O'Neill, S. and S. Nicholson-Cole, 2009: "Fear won't do it": promoting positive engagement with climate change through visual and iconic representations. *Science Communication*, **30**, 355-379.

Ogden, A.E. and J.L. Innes, 2009: Application of structured decision making to an assessment of climate change vulnerabilities and adaptation options for sustainable forest management. *Ecology and Society*, **14(1)**, 11, www.ecologyandsociety.org/vol14/iss2/art12/.

Ohlson, D.W., G.A. McKinnon, and K.G. Hirsch, 2005: A structured decision-making approach to climate change adaptation in the forest sector. *Forestry Chronicle*, **81**, 97-103.

Oreskes, N. and E.M. Conway, 2010: *Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues From Tobacco Smoke to Global Warming*, 1st U.S. edn., Bloomsbury Press, New York, NY, USA, 355 pp.

Orlove, B., 2009: The past, the present, and some possible futures of adaptation. In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, N., I. Lorenzoni, and K. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK, pp. 131-163.

Orlove, B. and M. Kabugo, 2005: Signs and sight in southern Uganda: representing perception in ordinary conversation. *Etnofoor*, **18**, 124-141.

Orlove, B., C. Roncoli, M. Kabugo, and A. Majugu, 2010: Indigenous climate knowledge in southern Uganda: the multiple components of a dynamic regional system. *Climatic Change*, **100**, 243-265.

Oskamp, S. and P.W. Schultz, 2006: Using psychological science to achieve sustainability. In: *Applied Psychology: New Frontiers and Rewarding Careers* [Donaldson, S., D. Berger, and K. Pezdek (eds.)]. Lawrence Erlbaum, Mahwah, NJ, USA, pp. 81-106.

Pahl-Wostl, C., 2007: Transitions towards adaptive management of water facing climate and global change. *Water Resources Management*, **21**, 49-62.

Park, S., N. Marshall, E. Jakku, A. Dowd, S. Howden, E. Mendham, and A. Fleming, 2012: Informing adaptation responses to climate change through theories of transformation. *Global Environmental Change*, **22**, 115-126.

Parry, M.L. and T.R. Carter, 1998: *Climate Impact and Adaptation Assessment: A Guide to the IPCC Approach*. Earthscan, London, UK, 166 pp.

Parson, E.A., 2008: Useful global-change scenarios: current issues and challenges. *Environmental Research Letters*, **3(4)**, 045016, doi:10.1088/1748-9326/3/4/045016.

Parson, E.A., V.R. Burkett, K. Fischer-Vanden, D.W. Keith, L.O. Mearns, H.M. Pitcher, C.E. Rosenweig, and M.D. Webster, 2007: *Global-Change Scenarios: Their Development and Use*. Sub-report 2.1B of Synthesis and Assessment Product 2.1 by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Department of Energy, Office of Biological & Environmental Research, Washington, DC, USA, 106 pp.

Paton, K. and P. Fairbairn-Dunlop, 2010: Listening to local voices: Tuvaluans respond to climate change. *Local Environment*, **15**, 687-698.

Patt, A. and S. Dessai, 2005: Communicating uncertainty: lessons learned and suggestions for climate change assessment. *Comptes Rendus Geoscience*, **337**, 425-441.

Patt, A.G. and D.P. Schrag, 2003: Using specific language to describe risk and probability. *Climatic Change*, **61**, 17-30.

Pearce, T.D., J.D. Ford, G.J. Laidler, B. Smit, F. Duerden, M. Allarut, M. Andrachuk, S. Baryluk, A. Dialla, P. Elee, A. Goose, T. Ikummaq, E. Joamie, F. Kataoyak, E. Loring, S. Meakin, S. Nickels, K. Shappa, J. Shirley, and J. Wandel, 2009: Community collaboration and climate change research in the Canadian Arctic. *Polar Research*, **28**, 10-27.

Pedlar, J.H., D.W. McKenney, I. Aubin, T. Beardmore, J. Beaulieu, L. Iverson, G.A. O'Neill, R.S. Winder, and C. Ste-Marie, 2012: Placing forestry in the assisted migration debate. *BioScience*, **62(9)**, 835-842.

Pelling, M., C. High, J. Dearing, and D. Smith, 2008: Shadow spaces for social learning: a relational understanding of adaptive capacity to climate change within organisations. *Environment and Planning A*, **40**, 867-884.

Peng, K. and R.E. Nisbett, 1999: Culture, dialectics, and reasoning about conradiction. *American Psychologist*, **54**, 741-754.

Pereira, Â.G. and S.C. Quintana, 2002: From technocratic to participatory decision support systems: responding to the new governance initiatives. *Journal of Geographic Information and Decision Analysis*, **6**, 95-107.

Perlovsky, L., 2009: Language and cognition. *Neural Networks*, **22**, 247-257.

Peschl, M.F., 2007: From double-loop learning to triple-loop learning profound change, individual cultivation, and the role of wisdom in the context of the microlearning approach. In: *Didactics of Microlearning: Concepts, Discourses and Examples* [Hug, T. (ed.)]. Waxman, Munster, Germany and New York, NY, USA, pp. 292-312.

Pidgeon, N. and B. Fischhoff, 2011: The role of social and decision sciences in communicating uncertain climate risks. *Nature Climate Change*, **1**, 35-41.

Pidgeon, N., R. Kasperson, and P. Slovic (eds.), 2003: *The Social Amplification of Risk*. Cambridge University Press, Cambridge, UK, 468 pp.

Pielke, R.A., 1998: Rethinking the role of adaptation in climate policy. *Global Environmental Change*, **8**, 159-170.

PIK, 2012: *4°C Turn Down the Heat: Why a 4°C Warmer World Must be Avoided.* A Report for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics (PIK), The World Bank, Washington, DC, USA, 84 pp.

Portier, C.J., K.T. Tart, S.R. Carter, C.H. Dilworth, A.E. Grambsch, J. Golke, J. Hess, S. Howard, G. Luber, and J. Lutz, 2010: *A Human Health Perspective on Climate Change: A Report Outlining the Research Needs on the Human Health Effects of Climate Change*. Environmental Health Perspectives and National Institute of Environmental Health Sciences, Research Triangle Park, NC, USA, 70 pp.

Posthumus, H., C.J.M. Hewett, J. Morris, and P.F. Quinn, 2008: Agricultural land use and flood risk management: engaging with stakeholders in North Yorkshire. *Agricultural Water Management*, **95**, 787-798.

Power, M., 2007: *Organized Uncertainty: Designing a World of Risk Management*. Oxford University Press, Oxford, UK and New York, NY, USA, 248 pp.

Preston, B., C. Brooke, T. Measham, T. Smith, and R. Gorddard, 2009: Igniting change in local government: lessons learned from a bushfire vulnerability assessment. *Mitigation and Adaptation Strategies for Global Change*, **14**, 251-283.

Preston, B.L., E. Yuen and R. Westaway, 2011: Putting vulnerability to climate change on the map: a review of approaches, benefits, and risks. *Sustainability Science*, **6**, 177-202.

Preston, B.L., J. Mustelin, and M.C. Maloney, 2013: Climate adaptation heuristics and the science/policy divide. *Mitigation and Adaptation Strategies for Global Change*, 31 pp. (in press), doi:10.1007/s11027-013-9503-x.

Pulwarty, R.S., C. Simpson, and C.R. Nierenberg, 2009: The Regional Integrated Sciences and Assessments (RISA) Program: crafting effective assessments for the long haul. In: *Integrated Regional Assessment of Global Climate Change* [Knight, C.G. and J. Jager (eds.)]. Cambridge University Press, Cambridge, UK, pp. 367-393.

Quay, R., 2010: Anticipatory governance: a tool for climate change adaptation. *Journal of the American Planning Association*, **76**, 496-511.

Raadgever, G.T., E. Mostert, and N.C. van de Giesen, 2008: Identification of stakeholder perspectives on future flood management in the Rhine basin using Q methodology. *Hydrology and Earth System Sciences*, **12**, 1097-1109.

Radford, L., 2009: Why do gestures matter? Sensuous cognition and the palpability of mathematical meanings. *Educational Studies in Mathematics*, **70**, 111-126.

Rajeev Gowda, M., J. Fox, and R. Magelky, 1997: Students' understanding of climate change: insights for scientists and educators. *Bulletin of the American Meteorological Society*, **78**, 2232-2240.

Ranger, N., A. Millner, S. Dietz, S. Fankhauser, A. Lopez, and G. Ruta, 2010: *Adaptation in the UK: A Decision Making Process*. Grantham/CCCEP Policy Brief, Environment Agency, London, UK, 61 pp.

Raskin, P., F. Monks, T. Ribeiro, D.van Vuuren, and M. Zurek, 2005: Global scenarios in historical perspective. In: *Ecosystems and Human Well-Being: Scenarios. Findings of the Scenarios Working Group, Millennium Ecosystem Assessment* [Carpenter, S.R., P.L. Pingali, E.M. Bennett, and M.B. Zurek (eds.)]. Island Press, Washington DC, USA pp. 35-44.

Reid, S., B. Smit, W. Caldwell, and S. Belliveau, 2007: Vulnerability and adaptation to climate risks in Ontario agriculture. *Mitigation and Adaptation Strategies for Global Change*, **12**, 609-637.

Renn, O., 2008: *Risk Governance: Coping With Uncertainty in a Complex World*. Earthscan, London, UK and Sterling, VA, USA, 455 pp.

Renn, O., 2011: The social amplification/attenuation of risk framework: application to climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **2**, 154-169.

Renn, O. and A. Klinke, 2004: Systemic risks: a new challenge for risk management. *EMBO reports*, **5**, S41-S46.

Renn, O., W.J. Burns, J.X. Kasperson, R.E. Kasperson, and P. Slovic, 1992: The social amplification of risk: theoretical foundations and empirical applications. *Journal of Social Issues*, **48**, 137-160.

Renn, O., A. Klinke, and M. van Asselt, 2011: Coping with complexity, uncertainty and ambiguity in risk governance: a synthesis. *Ambio*, **40**, 231-246.

Reser, J.P., S.A. Morrissey, and M. Ellul, 2011: The threat of climate change: psychological response, adaptation, and impacts. In: *Climate Change and Human Well-Being: Global Challenges And Opportunities* [Weissbecker, I. (ed.)]. Springer Science, New York, NY, USA, pp. 19-42.

Rickards, L. and S. Howden, 2012: Transformational adaptation: agriculture and climate change. *Crop and Pasture Science*, **63**, 240-250.

Rittel, H. and M. Webber, 1973: Dilemmas in a general theory of planning. *Policy Sciences*, **4**, 155-69.

Roberts, D., R. Boon, N. Diederichs, E. Douwes, N. Govender, A. Mcinnes, C. Mclean, S. O'Donoghue, and M. Spires, 2012: Exploring ecosystem-based adaptation in Durban, South Africa: "learning-by-doing" at the local government coal face. *Environment and Urbanization*, **24**, 167-195.

Robinson, J., M. Bradley, P. Busby, D. Connor, A. Murray, B. Sampson, and W. Soper, 2006: Climate change and sustainable development: realizing the opportunity. *AMBIO: A Journal of the Human Environment*, **35**, 2-8.

Roeser, S., 2012: Risk communication, public engagement, and climate change: a role for emotions. *Risk Analysis*, **32**, 1033-1040.

Rogers, R.W., 1975: A protection motivation theory of fear appeals and attitude change. *The Journal of Psychology*, **91**, 93-114.

Romsdahl, R. and C. Pyke, 2009: What does decision support mean to the climate change research community? *Climatic Change*, **95**, 1-10.

Roncoli, C., T. Crane, and B. Orlove, 2009: Fielding climate change in cultural anthropology. In: *Anthropology and Climate Change: From Encounters to Actions* [Crate, S.A. and M. Nuttall (eds.)]. Left Coast Press, San Francisco, CA, USA, pp. 87-115.

Rosa, E., 2003: The logical structure of the social amplification of risk framework (SARF): metatheoretical foundations and policy implications. In: *The Social Amplification of Risk* [Pidgeon, N., R. Kasperson, and P. Slovic (eds.)]. Cambridge University Press, Cambridge, UK, pp. 46-76.

Rosa, E.A., 2008: White, black, and gray: critical dialogue with the International Risk Governance Council's Framework for Risk Governance. In: *Global Risk Governance* [Bunting, C. (ed.)]. Vol. 1, Springer, Dordrecht, Netherlands, pp. 101-118.

Rosenau, J.N., 2005: Strong demand, huge supply: governance in an emerging epoch. In: *Multi-level Governance* [Bache, I. and M. Flinders (eds.)]. Oxford University Press, Oxford, UK, pp. 31-48.

Rosenhead, J., 1989: *Rational Analysis for a Problematic World: Problem Structuring Methods for Complexity, Uncertainty, and Conflict*. John Wiley & Sons, Chichester, UK and New York, NY, USA, 370 pp.

Rosenzweig, C., W.D. Solecki, S.A. Hammer, and S. Mehrotra, (eds.), 2011: *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network*. Cambridge University Press, Cambridge, UK, 312 pp.

Rudiak-Gould, P., 2011: Climate change and anthropology: the importance of reception studies. *Anthropology Today*, **27**, 9-12.

Ruhl, J., 2010a: Climate change adaptation and the structural transformation of environmental law. *Environmental Law*, **40**, 363-431.

Ruhl, J., 2010b: General design principles for resilience and adaptive capacity in legal systems – with applications to climate change adaptation. *North Carolina Law Review*, **89**, 1373-1401.

Ruttan, V.W., D.E. Bell, and W.C. Clark, 1994: Climate change and food security: agriculture, health and environmental research. *Global Environmental Change*, **4**, 63-77.

Saavedra, C. and W.W. Budd, 2009: Climate change and environmental planning: working to build community resilience and adaptive capacity in Washington State, USA. *Habitat International*, **33**, 246-252.

Salter, J., J. Robinson, and A. Wiek, 2010: Participatory methods of integrated assessment – a review. *Wiley Interdisciplinary Reviews: Climate Change*, **1**, 697-717.

Sandler, R., 2009: The value of species and the ethical foundations of assisted colonization. *Conservation Biology*, **24**, 424-431.

Sarewitz, D. and R.A. Pielke Jr, 2007: The neglected heart of science policy: reconciling supply of and demand for science. *Environmental Science & Policy*, **10**, 5-16.

Scannell, L. and R. Gifford, 2013: Personally relevant climate change: the role of place attachment and local versus global message framing in engagement. *Environment and Behavior*, **45**, 60-85.

Schaffrin, A., 2011: No measure without concept. a critical review on the conceptualization and measurement of environmental concern. *International Review of Social Research*, **1**, 11-31.

Schalow, F., 2000: Who speaks for the animals? Heidegger and the question of animal welfare. *Environmental Ethics*, **22**, 259-272.

Schipper, E.L.F., 2007: *Climate Change Adaptation and Development: Exploring the Linkages*. Tyndall Centre for Climate Change Research Working Paper 107, Tyndall Centre for Climate Change Research, Norwich, UK, 20 pp.

Schneider, S.H., S. Semenov, A. Patwardhan, I. Burton, C.H.D. Magadza, M. Oppenheimer, A.B. Pittock, A. Rahman, J.B. Smith, A. Suarez, and F. Yamin, 2007: Assessing key vulnerabilities and the risk from climate change. In: *Climate Change 2007: Impacts, Adaptation And Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 779-810.

Schroth, O., E. Pond, C. Campbell, P. Cizek, S. Bohus, and S.R.J. Sheppard, 2011: Tool or toy? Virtual globes in landscape planning. *Future Internet*, **3**, 204-227.

Schultz, W.P., C. Shriver, J.J. Tanbanico, and A.M. Khazian, 2004: Implicit connections with nature. *Journal of Environmental Psychology*, **24**, 31-42.

Semazzi, F.H.M., 2011: Framework for climate services in developing countries. *Climate Research*, **47**, 145-150.

Sen, A.K., 2009: *The Idea of Justice*. Harvard University Press, Cambridge, MA, USA, 496 pp.

Seppälä, R., A. Buck, and P. Katila (eds.), 2009: *Adaptation of Forests and People to Climate Change. A Global Assessment Report.* International Union of Forest Research Organizations (IUFRO), Helsinki, Finland, 224 pp.

Shafer, M.A., 2004: Climate services: where do we go from here? In: *Proceedings of the 14th Conference on Applied Climatology, Seattle, WA, January 11-15*. American Meterological Society, Boston, MA, USA, 9 pp., ams.confex.com/ams/84Annual/techprogram/paper_72822.htm.

Shaw, A., S. Sheppard, S. Burch, D. Flanders, A. Wiek, J. Carmichael, J. Robinson, and S. Cohen, 2009: Making local futures tangible – synthesizing, downscaling, and visualizing climate change scenarios for participatory capacity building. *Global Environmental Change*, **19**, 447-463.

Shepherd, P., J. Tansey, and H. Dowlatabadi, 2006: Context matters: what shapes adaptation to water stress in the Okanagan? *Climatic Change*, **78**, 31-62.

Sheppard, S.R.J., 2012: *Visualizing Climate Change: A Guide to Visual Communication of Climate Change and Developing Local Solutions*. Earthscan/Routledge, London, UK, 514 pp.

Sheppard, S.R.J., A. Shaw, D. Flanders, S. Burch, A. Wiek, J. Carmichael, J. Robinson, and S. Cohen, 2011: Future visioning of local climate change: a framework for community engagement and planning with scenarios and visualisation. *Futures*, **43**, 400-412.

Shwom, R., A. Dan, and T. Dietz, 2008: The effects of information and state of residence on climate change policy preferences. *Climatic Change*, **90**, 343-358.

Sivakumar, M., P. Bessemoulin, T.C. Peterson, and G. Asrar, 2011: Changing climate and demands for sustainable development. *Climate Research*, **47**, 3-4.

Smit, B. and J. Wandel, 2006: Adaptation, adaptive capacity and vulnerability. *Global Environmental Change*, **16**, 282-292.

Snover, A.K., L. Whitely Binder, J. Lopez, E. Willmott, J. Kay, D. Howell, and J. Simmonds, 2007: *Preparing for Climate Change: A Guidebook for Local, Regional and State Governments*. ICLEI-Local Government for Sustainability, Oakland, CA, USA, 172 pp.

Soyez, K., S. Hoffmann, S. Wünschmann, and K. Gelbrich, 2009: Proenvironmental value orientation across cultures. *Social Psychology*, **40**, 222-233.

Spence, A., W. Poortinga, and N. Pidgeon, 2012: The psychological distance of climate change. *Risk Analysis*, **32**, 957-972.

Stafford Smith, M., L. Horrocks, A. Harvey, C. Hamilton, M.S. Smith, L. Horrocks, A. Harvey, and C. Hamilton, 2011: Rethinking adaptation for a 4°C world. *Philosophical Transactions of the Royal Society A*, **369**, 196-216.

Steel, P. and C.J. König, 2006: Integrating theories of motivation. *Academy of Management Review*, **31**, 889-913.

Sterman, J.D. and L.B. Sweeney, 2007: Understanding public complacency about climate change: adults' mental models of climate change violate conservation of matter. *Climatic Change*, **80**, 213-238.

Stern, N., 2008: The economics of climate change – Richard T. Ely lecture. *American Economic Review: Papers & Proceedings*, **98**, 1-37.

Stern, N.H. and Treasury of Great Britain, 2007: *The Economics of Climate Change: The Stern Review*. Cambridge University Press, Cambridge, UK and New York, NY, USA, 692 pp.

Stern, P.C. and T. Dietz, 1994: The value basis of environmental concern. *Journal of Social Issues*, **50**, 65-84.

Stewart, N. and K. Simpson, 2008: A decision-by-sampling account of decision under risk. In: *The Probabilistic Mind: Prospects for Bayesian Cognitive Science* [Chater, N. and M. Oaksford (eds.)]. Oxford University Press, Oxford, UK, pp. 261-276.

Stewart, N., N. Chater, and G.D. Brown, 2006: Decision by sampling. *Cognitive Psychology*, **53**, 1-26.

Strauss, S., 2009: Global models, local risks: responding to climate change in the Swiss Alps. In: *Anthropology & Climate Change. From Encounters to Actions* [Crate, S.A. and M. Nuttall (eds.)]. Left Coast Press, Walnut Creek, CA, USA, pp. 166-174.

Strauss, S. and B. Orlove, 2003: Up in the air: the anthropology of weather and climate. In: *Weather, Climate and Culture* [Strauss, S. and B. Orlove (eds.)]. Berg, Oxford, UK and New York, NY, USA, pp. 3-14.

Strohschneider, S. and D. Güss, 1999: The fate of the Moros: a cross-cultural exploration of strategies in complex and dynamic decision making. *International Journal of Psychology*, **34**, 235-252.

Sundblad, E.-L., A. Biel, and T. Gärling, 2009: Knowledge and confidence in knowledge about climate change among experts, journalists, politicians, and laypersons. *Environment and Behavior*, **41**, 281-302.

Swanson, D., H. Venema, S. Barg, S. Tyler, J. Drexage, P. Bhandari, and U. Kelkar, 2006: Initial conceptual framework and literature review for understanding adaptive policies. In: *Designing Policies in a World of Uncertainty, Change, and Surprise: Adaptive Policy-Making for Agriculture and Water Resources in the Face of Climate Change* [Swanson, D. and U. Kelkar (eds.)]. International Institute for Sustainable Development (IISD), Winnipeg, Manitoba, Canada, and The Energy and Resources Institute (TERI), New Delhi, India, pp. 9-36.

Swanson, D., S. Barg, S. Tyler, H. Venema, S. Tomar, S. Bhadwal, S. Nair, I. Roy and J. Drexage, 2012: Seven tools for creating adaptive policies. *Technological Forecasting & Social Change*, **77**, 924-939.

Swim, J., S. Clayton, T. Doherty, R. Gifford, G. Howard, J. Reser, P. Stern, and E. Weber, 2010: *Psychology and Global Climate Change: Addressing a Multi-Faceted Phenomenon and Set of Challenges.* A Report by the American Psychological Association's Task Force on the Interface Between Psychology and Global Climate Change, American Psychological Association, Washington DC, USA, 108 pp.

Swim, J.K., P.C. Stern, T.J. Doherty, S. Clayton, J.P. Reser, E.U. Weber, R. Gifford, and G.S. Howard, 2011: Psychology's contributions to understanding and addressing global climate change. *American Psychologist*, **66**, 241-250.

Thompson, A. and J. Bendik-Keymer, 2012: *Ethical Adaptation to Climate Change: Human Virtues of the Future*. MIT Press, Cambridge. MA, USA, 344 pp.

Thompson, P.B., 1986: The philosophical foundations of risk. *Southern Journal of Philosophy*, **24**, 273-286.

Tobler, C., V.H.M. Visschers, and M. Siegrist, 2012: Addressing climate change: determinants of consumers' willingness to act and to support policy measures. *Journal of Environmental Psychology*, **32**, 197-207.

Tompkins, E.L., R. Few, and K. Brown, 2008a: Scenario-based stakeholder engagement: incorporating stakeholders preferences into coastal planning for climate change. *Journal of Environmental Management*, **88**, 1580-1592.

Tompkins, E.L., M.C. Lemos, and E. Boyd, 2008b: A less disastrous disaster: managing response to climate-driven hazards in the Cayman Islands and NE Brazil. *Global Environmental Change: Human and Policy Dimensions*, **18**, 736-745.

Tschakert, P. and K.A. Dietrich, 2010: Anticipatory learning for climate change adaptation and resilience. *Ecology and Society*, **15(2)**, 11, www.ecologyandsociety.org/vol15/iss2/art11/.

Tsosie, R., 2007: Indigenous people and environmental justice: the impact of climate change. *University of Colorado Law Review*, **78**, 1625-1677.

Turner, N.J. and H. Clifton, 2009: "It's so different today": climate change and indigenous lifeways in British Columbia, Canada. *Global Environmental Change*, **19**, 180-190.

Turnquist, M. and E. Vugrin, 2013: Design for resilience in infrastructure distribution networks. *Environment Systems & Decisions*, **33**, 104-120.

Tversky, A. and D. Kahneman, 1992: Advances in prospect theory: cumulative representation of uncertainty. *Journal of Risk and Uncertainty*, **5**, 297-323.

Tyler, S. and M. Moench, 2012: A framework for urban climate resilience. *Climate and Development*, **4**, 311-326.

Ulloa, A., 2011: Construcciones culturales sobre el clima. In: *Perspectivas Culturales del Clima* [Ulloa, A. (ed.)]. Universidad Nacional de Colombia, Instituto Latinoamericano para una Sociedad y un Derechos Alternativos (ILSA), Bogotá, Colombia, pp. 33-54.

UN, 1992: *United Nations Framework Convention on Climate Change (UNFCCC)*. United Nations, Geneva, Switzerland, 33 pp.

UNDP, 2005: *Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies and Measures*. United Nations Development Programme (UNDP), Cambridge University Press, Cambridge, UK and New York, NY, USA, 268 pp.

UNFCCC, 2009: *Potential Costs and Benefits of Adaptation Options: A Review of Existing Literature*. Technical Paper 2009/2, United Nations Framework Convention on Climate Change (UNFCCC), Geneva, Switzerland, 80 pp.

UNFCCC, 2012: *NAPA Priorities Database*. United Nations Framework Convention on Climate Change (UNFCCC), Bonn, Germany, unfccc.int/cooperation_support/least_developed_countries_portal/napa_priorities_database/ items/4583.php (accessed 28 Nov. 2012).

UNFCCC, 2013: *Report of the Conference of the Parties on Its Eighteenth Session, Held in Doha from 26 November to 8 December 2012. Addendum Part Two: Action Taken by the Conference of the Parties at Its Eighteenth Session*. United Nations Framework Convention on Climate Change (UNFCCC), United Nations, Geneva, Switzerland, 37 pp.

UNISDR, 2007: *Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters*. United Nations International Strategy for Disaster Reduction (UNISDR) and United Nations Development Programme (UNDP), Geneva, Switzerland, 24 pp.

UNISDR, 2011: *Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters. Mid-Term Review 2010-2011*. United Nations International Strategy for Disaster Reduction (UNISDR) and United Nations Development Programme (UNDP), Geneva, Switzerland, 107 pp.

UNISDR, 2012: *Making Cities Resilient Report 2012. My City Is Getting Ready! A Global Snapshot of How Local Governments Reduce Disaster Risk*. United Nations International Strategy for Disaster Reduction (UNISDR) and United Nations Development Programme (UNDP), Geneva, Switzerland,112 pp.

UNISDR and UNDP, 2012: *Disaster Risk Reduction and Climate Change Adaptation in the Pacific: An Institutional and Policy Analysis*. United Nations International Strategy for Disaster Reduction (UNISDR) and United Nations Development Programme (UNDP), Suva, Fiji, 76 pp.

van Asselt, M.B.A. and J. Rotmans, 2002: Uncertainty in integrated assessment modelling – from positivism to pluralism. *Climatic Change*, **54**, 75-105.

van Notten, P., 2006: Scenario development: a typology of approaches. In: *Schooling for Tomorrow: Think Scenarios, Rethink Education*. OECD Publishing, Paris, France, pp. 66-92.

van Ruijven, B.J., M.A. Levy, A. Agrawal, F. Biermann, J. Birkmann, T.R. Carter, K.L. Ebi, M. Garschagen, B. Jones, and R. Jones, 2013: Enhancing the relevance of Shared Socioeconomic Pathways for climate change impacts, adaptation and vulnerability research. In: Special Issue of *Climatic Change: A Framework for the Development of New Socio-economic Scenarios for Climate Change Research* [Nakicenovic, N., R. Lempert, and A. Janetos, (eds.)]. 14 pp. (in press), doi:10.1007/s10584-013-0931-0.

Varady, R.G., C.A. Scott, M. Wilder, B. Morehouse, N.P. Pablos, and G.M. Garfin, 2012: Transboundary adaptive management to reduce climate-change vulnerability in the western U.S.-Mexico border region. *Environmental Science & Policy*, **26**, 102-112.

Vedwan, N., 2006: Culture, climate and the environment: local knowledge and perception of climate change among apple growers in northwestern India. *Journal of Ecological Anthropology*, **10**, 4-18.

Verschuuren, J., 2013: *Research Handbook on Climate Change Adaptation Law*. Edward Elgar Publishing, Cheltenham, UK and Northampton, MA, USA, 456 pp.

Visbeck, M., 2008: From climate assessment to climate services. *Nature Geoscience*, **1**, 2-3.

Vogel, C., S.C. Moser, R.E. Kasperson, and G.D. Dabelko, 2007: Linking vulnerability, adaptation, and resilience science to practice: pathways, players, and partnerships. *Global Environmental Change: Human and Policy Dimensions*, **17**, 349-364.

von Storch, H., I. Meinke, N. Stehr, B. Ratter, W. Krauss, R.A. Pielke Jr, R. Grundmann, M. Reckermann, and R. Weisse, 2011: Regional climate services: illustrated with experiences from Northern Europe. *Zeitschrift für Umweltpolitik & Umweltrecht*, **34(1)**, 1-15.

Vugrin, E.D., D.E. Warren, and M.A. Ehlen, 2011: A resilience assessment framework for infrastructure and economic systems: quantitative and qualitative resilience analysis of petrochemical supply chains to a hurricane. *Process Safety Progress*, **30**, 280-290.

Walker, W.E., S.A. Rahman and J. Cave, 2001: Adaptive policies, policy analysis, and policy-making. *European Journal of Operational Research*, **128**, 282-289.

Walker, W.E., P. Harremoës, J. Rotmans, J.P. van der Sluijs, M.B.A. van Asselt, P. Janssen, and M.P.K. von Krauss, 2003: Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support. *Integrated Assessment*, **4**, 5-17.

Webb, R. and J.-l. Beh, 2013: *Leading Adaptation Practices and Support Strategies for Australia: An International and Australian Review of Products and Tools*. National Climate Change Adaptation Research Facility (NCCARF), Gold Coast, Australia, 106 pp.

Weichselgartner, J., 2001: Disaster mitigation: the concept of vulnerability revisited. *Disaster Prevention and Management*, **10**, 85-95.

Westerhoff, L. and J. Robinson, 2013: *The Meaning(s) of Climate Change: Exploring Narrative and Social Practice in the Quest for Transformation*. IRES Working Paper Series, No. 2013-01, Institute for Resources, the Environment and Sustainability, Vancouver, BC, Canada, 20 pp.

White, D.D., A. Wutich, K.L. Larson, P. Gober, T. Lant, and C. Senneville, 2010: Credibility, salience, and legitimacy of boundary objects: water managers' assessment of a simulation model in an immersive decision theater. *Science and Public Policy*, **37**, 219-232.

WHO, 2008: *Heat-Health Action Plans*. World Health Organization (WHO), Geneva, Switzerland, 58 pp.

Wijewardana, D., 2008: Criteria and indicators for sustainable forest management: the road travelled and the way ahead. *Ecological Indicators*, **8**, 115-122.

Wilby, R.L. and S. Dessai, 2010: Robust adaptation to climate change. *Weather*, **65**, 180-185.

Wilby, R.L. and I. Harris, 2006: A framework for assessing uncertainties in climate change impacts: low-flow scenarios for the River Thames, UK. *Water Resources Research*, **42(2)**, W02419, doi:10.1029/2005WR004065.

Wilkinson, A. and E. Eidinow, 2008: Evolving practices in environmental scenarios: a new scenario typology. *Environmental Research Letters*, **3**, 045017, doi:10.1088/1748-9326/3/4/045017.

Willows, R. and R. Connell, 2003: *Climate Adaptation: Risk, Uncertainty, and Decision-making*. UKCIP Technical Report, UK Climate Impacts Programme (UKCIP), Oxford, UK, 154 pp.

Wilson, C. and T. McDaniels, 2007: Structured decision-making to link climate change and sustainable development. *Climate Policy*, **7**, 353-370.

WMO, 2011: *Climate Knowledge for Action: A Global Framework for Climate Services – Empowering the Most Vulnerable*. Report No. 1065, World Meteorological Organization (WMO), Geneva, Switzerland, 248 pp.

Wolf, J., I. Allice, and T. Bell, 2012: Values, climate change, and implications for adaptation: evidence from two communities in Labrador, Canada. *Global Environmental Change*, **28**, 548-562.

Woods, R., A. Fernández, and S. Coen, 2012: The use of religious metaphors by UK newspapers to describe and denigrate climate change. *Public Understanding of Science*, **21**, 323-339.

World Resources Institute, UNDP, UNEP, and World Bank, 2011: *World Resources 2010–2011: Decision Making in a Changing Climate – Adaptation Challenges and Choices*. World Resources Institute (WRI), Washington, DC, USA, 172 pp.

Worthington, S.A. and T. Pipa, 2010: International NGOs and foundations: essential partners in creating an effective architecture for aid. In: *Making Development Aid More Effective. The 2010 Brookings Blum Roundtable Policy Briefs*. Brooking Institute, New York, NY, USA, pp. 28-36.

Wright, C. and D. Nyberg, 2012: Working with passion: emotionology, corporate environmentalism and climate change. *Human Relations*, **65**, 1561-1587.

WUCA, 2010: *Decision Support Planning Methods: Incorporating Climate Change Uncertainties into Water Planning*. Water Utility Climate Alliance (WUCA), San Francisco, CA, USA, 102 pp.

Wynne, B., 2002: Risk and environment as legitimatory discourses of technology: reflexivity inside out? *Current Sociology*, **50**, 459-477.

Xiao, C. and R.E. Dunlap, 2007: Validating a comprehensive model of environmental concern cross-nationally: a U.S.-Canadian comparison. *Social Science Quarterly*, **88**, 471-493.

Yearley, S., 2009: Sociology and climate change after Kyoto: what roles for social science in understanding climate change? *Current Sociology*, **57**, 389-405.

Yohe, G.W., R.D. Lasco, Q.K. Ahmad, N.W. Arnell, S.J. Cohen, C. Hope, A.C. Janetos, and R.T. Perez, 2007: Perspectives on climate change and sustainability. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J.v.d. Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 811-841.

Young, C.K., 2013: The problem-solution adaptation implementation framework summary. In: *Valuing Adaptation under Rapid Change* [Jones, R.N., C.K. Young, J. Handmer, A. Keating, G.D. Mekala, and P. Sheehan (eds.)]. National Climate Change Adaptation Research Facility (NCCARF), Gold Coast, Australia, pp. 152-156.

Young, O.R., L.A. King, and H. Schroeder, 2008: *Institutions and Environmental Change: Principal Findings, Applications, and Research Frontiers*. MIT Press, Cambridge, MA, USA, 373 pp.

Zhou, S., A.D. Smith, A.E. Punt, A.J. Richardson, M. Gibbs, E.A. Fulton, S. Pascoe, C. Bulman, P. Bayliss, and K. Sainsbury, 2010: Ecosystem-based fisheries management requires a change to the selective fishing philosophy. *Proceedings of the National Academy of Sciences of the United States of America*, **107**, 9485-9489.

Ziervogel, G. and F. Zermoglio, 2009: Climate change scenarios and the development of adaptation strategies in Africa: challenges and opportunities. *Climate Research*, **40**, 133-146.

3 Freshwater Resources

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This chapter should be cited as:
Jiménez Cisneros, B.E., T. Oki, N.W. Arnell, G. Benito, J.G. Cogley, P. Döll, T. Jiang, and S.S. Mwakalila, 2014: Freshwater resources. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 229-269.

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Executive Summary

Key Risks at the Global Scale

Freshwater-related risks of climate change increase significantly with increasing greenhouse gas (GHG) concentrations (*robust evidence*, *high agreement*). {3.4, 3.5} Modeling studies since AR4, with large but better quantified uncertainties, have demonstrated clear differences between global futures with higher emissions, which have stronger adverse impacts, and those with lower emissions, which cause less damage and cost less to adapt to. {Table 3-2} For each degree of global warming, approximately 7% of the global population is projected to be exposed to a decrease of renewable water resources of at least 20% (multi-model mean). By the end of the 21st century, the number of people exposed annually to the equivalent of a 20th-century 100-year river flood is projected to be three times greater for very high emissions (Representative Concentration Pathway 8.5 (RCP8.5)) than for very low emissions (RCP2.6) (multi-model mean) for the fixed population distribution at the level in the year 2005. {Table 3-2, 3.4.8}

Climate change is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions (*robust evidence*, *high agreement*). {3.4, 3.5} This will intensify competition for water among agriculture, ecosystems, settlements, industry, and energy production, affecting regional water, energy, and food security (*limited evidence*, *medium* to *high agreement*). {3.5.1, 3.5.2, Box CC-WE} In contrast, water resources are projected to increase at high latitudes. Proportional changes are typically one to three times greater for runoff than for precipitation. The effects on water resources and irrigation requirements of changes in vegetation due to increasing GHG concentrations and climate change remain uncertain. {Box CC-VW}

So far there are no widespread observations of changes in flood magnitude and frequency due to anthropogenic climate change, but projections imply variations in the frequency of floods (*limited evidence*, *medium agreement*). Flood hazards are projected to increase in parts of South, Southeast, and Northeast Asia; tropical Africa; and South America (*limited evidence*, *medium agreement*). Since the mid-20th century, socioeconomic losses from flooding have increased mainly due to greater exposure and vulnerability (*high confidence*). Global flood risk will increase in the future partly due to climate change (*limited evidence*, *medium agreement*). {3.2.7, 3.4.8}

Climate change is *likely* to increase the frequency of meteorological droughts (less rainfall) and agricultural droughts (less soil moisture) in presently dry regions by the end of the 21st century under the RCP8.5 scenario (*medium confidence*). {WGI AR5 Chapter 12} This is *likely* to increase the frequency of short hydrological droughts (less surface water and groundwater) in these regions (*medium evidence*, *medium agreement*). {3.4.8} Projected changes in the frequency of droughts longer than 12 months are more uncertain, because these depend on accumulated precipitation over long periods. There is no evidence that surface water and groundwater drought frequency has changed over the last few decades, although impacts of drought have increased mostly due to increased water demand. {3.5.1}

Climate change negatively impacts freshwater ecosystems by changing streamflow and water quality (*medium evidence*, *high agreement*). Quantitative responses are known in only a few cases. Except in areas with intensive irrigation, the streamflow-mediated ecological impacts of climate change are expected to be stronger than historical impacts owing to anthropogenic alteration of flow regimes by water withdrawals and the construction of reservoirs. {Box CC-RF, 3.5.2.4}

Climate change is projected to reduce raw water quality, posing risks to drinking water quality even with conventional treatment (*medium evidence*, *high agreement*). The sources of the risks are increased temperature, increases in sediment, nutrient and pollutant loadings due to heavy rainfall, reduced dilution of pollutants during droughts, and disruption of treatment facilities during floods. {3.2.5, Figure 3-2, 3.4.6, 3.5.2.3}

In regions with snowfall, climate change has altered observed streamflow seasonality, and increasing alterations due to climate change are projected (*robust evidence*, *high agreement*). {Table 3-1, 3.2.3, 3.2.7, 3.4.5, 3.4.6, 26.2.2} Except in very cold regions, warming in the last decades has reduced the spring maximum snow depth and brought forward the spring maximum of snowmelt discharge; smaller snowmelt floods, increased winter flows, and reduced summer low flows have all been observed. River ice in Arctic rivers has been observed to break up earlier. {3.2.3, 28.2.1.1}

Because nearly all glaciers are too large for equilibrium with the present climate, there is a committed water resources change during much of the 21st century, and changes beyond the committed change are expected due to continued warming; in glacier-fed rivers, total meltwater yields from stored glacier ice will increase in many regions during the next decades but decrease thereafter (*robust evidence*, *high agreement*). Continued loss of glacier ice implies a shift of peak discharge from summer to spring, except in monsoonal catchments, and possibly a reduction of summer flows in the downstream parts of glacierized catchments. {3.4.3}

There is little or no observational evidence yet that soil erosion and sediment loads have been altered significantly due to changing climate (*limited evidence*, *medium agreement*). However, increases in heavy rainfall and temperature are projected to change soil erosion and sediment yield, although the extent of these changes is highly uncertain and depends on rainfall seasonality, land cover, and soil management practices. {3.2.6, 3.4.7}

Adaptation, Mitigation, and Sustainable Development

Of the global cost of water sector adaptation, most is necessary in developing countries where there are many opportunities for anticipatory adaptation (*medium evidence*, *high agreement*). There is limited published information on the water sector costs of adaptation at the local level. {3.6.1, 3.6.3}

An adaptive approach to water management can address uncertainty due to climate change (*limited evidence*, *high agreement*). Adaptive techniques include scenario planning, experimental approaches that involve learning from experience, and the development of flexible and low-regret solutions that are resilient to uncertainty. Barriers to progress include lack of human and institutional capacity, financial resources, awareness, and communication. {3.6.1, 3.6.2, 3.6.4}

Reliability of water supply, which is expected to suffer from increased variability of surface water availability, may be enhanced by increased groundwater abstractions (*limited evidence*, *high agreement*). This adaptation to climate change is limited in regions where renewable groundwater resources decrease due to climate change. {3.4.5, 3.4.8, 3.5.1}

Some measures to reduce GHG emissions imply risks for freshwater systems (*medium evidence*, *high agreement*). If irrigated, bioenergy crops make water demands that other mitigation measures do not. Hydropower has negative impacts on freshwater ecosystems, which can be reduced by appropriate management. Carbon capture and storage can decrease groundwater quality. In some regions, afforestation can reduce renewable water resources but also flood risk and soil erosion. {3.7.2.1, Box CC-WE}

3.1. Introduction

Changes in the hydrological cycle due to climate change can lead to diverse impacts and risks, and they are conditioned by and interact with non-climatic drivers of change and water management responses (Figure 3-1). Water is the agent that delivers many of the impacts of climate change to society, for example, to the energy, agriculture, and transport sectors. Even though water moves through the hydrological cycle, it is a locally variable resource, and vulnerabilities to water-related hazards such as floods and droughts differ between regions. Anthropogenic climate change is one of many stressors of water resources. Non-climatic drivers such as population increase, economic development, urbanization, and land use or natural geomorphic changes also challenge the sustainability of resources by decreasing water supply or increasing demand. In this context, adaptation to climate change in the water sector can contribute to improving the availability of water.

The key messages with *high* or *very high confidence* from the Working Group II Fourth Assessment Report (AR4; IPCC, 2007) in respect to freshwater resources were:

- The observed and projected impacts of climate change on freshwater systems and their management are due mainly to increases in temperature and sea level, local changes of precipitation, and changes in the variability of those quantities.
- Semiarid and arid areas are particularly exposed.
- Warmer water, more intense precipitation, and longer periods of low flow reduce water quality, with impacts on ecosystems, human health, and reliability and operating costs of water services.
- Climate change affects water management infrastructure and practice.
- Adaptation and risk management practices have been developed for the water sector in some countries and regions.
- The negative impacts of climate change on freshwater systems outweigh its benefits.

This chapter assesses hydrological changes due to climate change, based mainly on research published since AR4. Current gaps in research and data are summarized in Section 3.8. For further information on observed trends in the water cycle, please see Chapter 2 of the Working Group I (WGI) contribution to this assessment. See WGI AR5 Chapter 4 for freshwater in cold regions and WGI AR5 Chapters 10 for detection and attribution, 11 for near-term projections, and 12 for long-term projections of climate change. In this Working Group II contribution, impacts on aquatic ecosystems are discussed in Chapter 4 (see also Section 3.5.2.4). Chapter 7 describes the impacts of climate change on food production (see also Section 3.5.2.1 for the impact of hydrological changes on the agricultural sector). The health effects of changes in water quality and quantity are covered in Chapter 11, and regional vulnerabilities related to freshwater in Chapters 21 to 30. Sections 3.2.7, 3.4.8, and 3.6.3 discuss impact and adaptation costs related to water resources; these costs are assessed more broadly in Chapter 10.

3.2. Observed Hydrological Changes Due to Climate Change

3.2.1. Detection and Attribution

A documented hydrological change is not necessarily due to anthropogenic climate change. Detection entails showing, usually statistically, that part

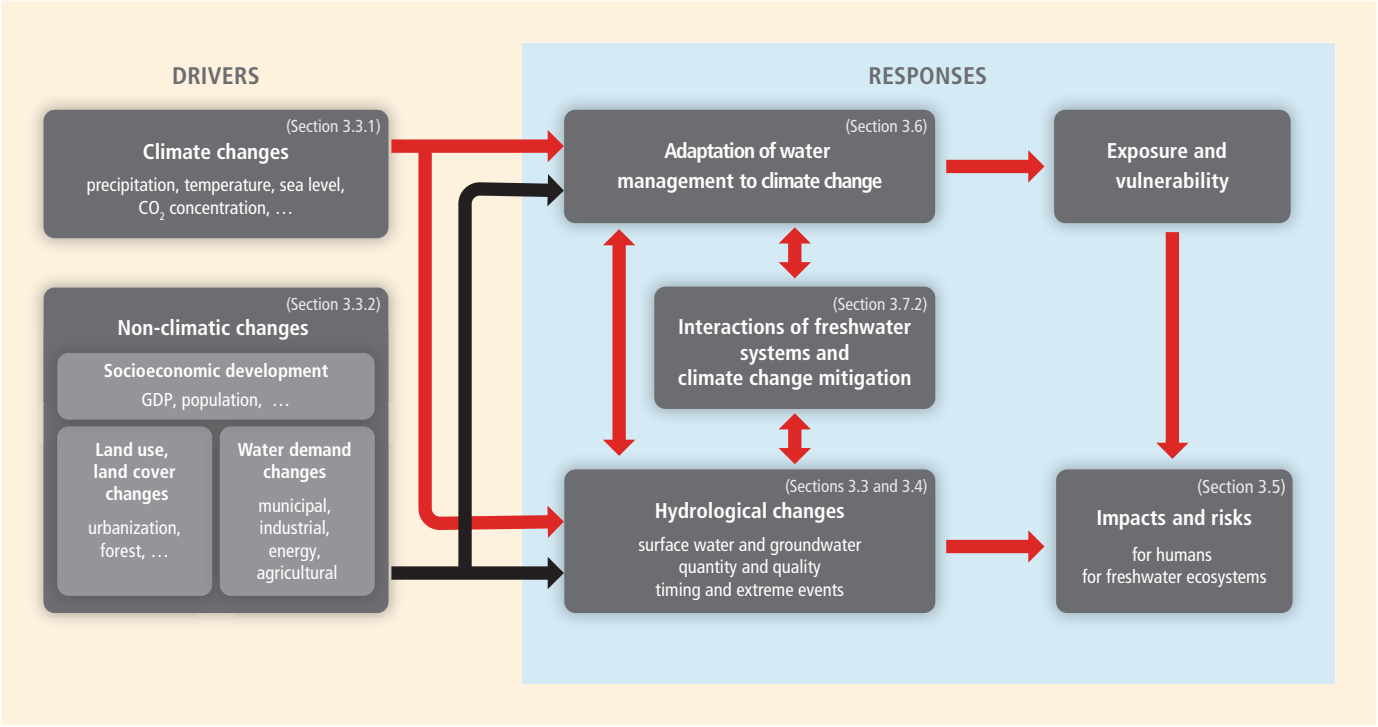
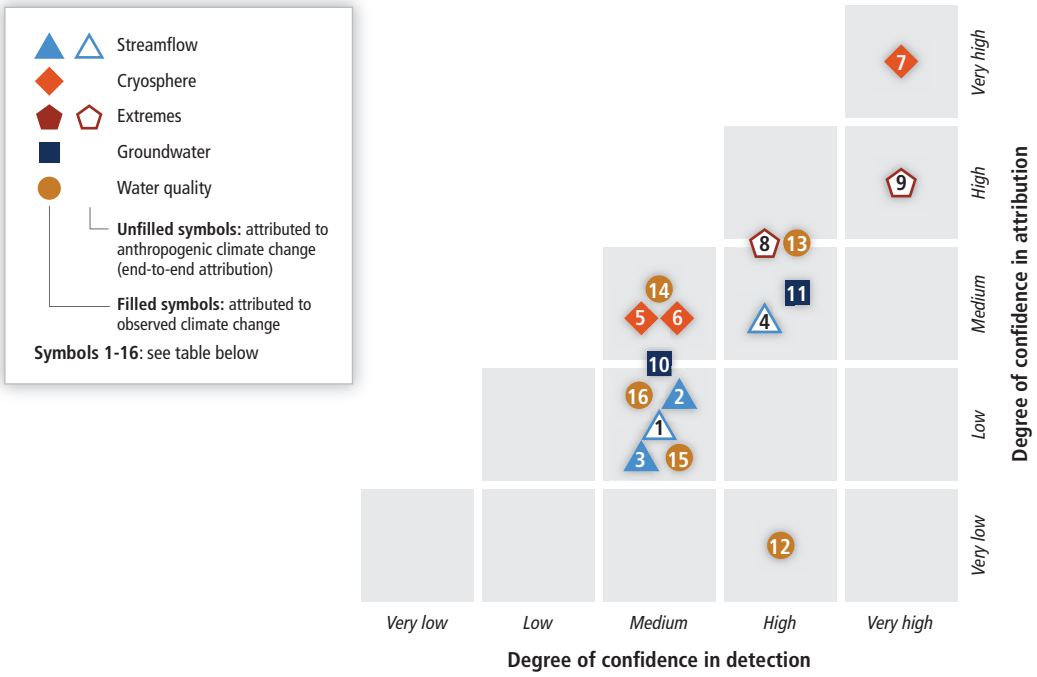


Figure 3-1 | Framework (boxes) and linkages (arrows) for considering impacts of climatic and social changes on freshwater systems, and consequent impacts on and risks for humans and freshwater ecosystems. Both climatic (Section 3.3.1) and non-climatic (Section 3.3.2) drivers have changed natural freshwater systems (Section 3.2) and are expected to continue to do so (Section 3.4). They also stimulate adaptive measures (Section 3.6). Hydrological and water management changes interact with each other and with measures to mitigate climate change (Section 3.7.2). Adaptive measures influence the exposure and vulnerability of human beings and ecosystems to water-related risks (Section 3.5).

Table 3-1 | Selected examples, mainly from Section 3.2, of the observation, detection, and attribution of impacts of climate change on freshwater resources. Observed hydrological changes are attributed here to their climatic drivers, not all of which are necessarily anthropogenic.



	Observed change	Attributed to	Reference
1	Changed runoff (global, 1960–1994)	Mainly climatic change, and to a lesser degree CO_2 increase and land use change	Gerten et al. (2008); Piao et al. (2007); Alkama et al. (2011)
2	Reduced runoff (Yellow River, China)	Increased temperature; only 35% of reduction attributable to human withdrawals	Piao et al. (2010)
3	Earlier annual peak discharge (Russian Arctic, 1960–2001)	Increased temperature and earlier spring thaw	Shiklomanov et al. (2007)
4	Earlier annual peak discharge (Columbia River, western USA, 1950–1999)	Anthropogenic warming	Hidalgo et al. (2009)
5	Glacier meltwater yield greater in 1910–1940 than in 1980–2000 (European Alps)	Glacier shrinkage forced by comparable warming rates in the two periods	Collins (2008)
6	Decreased dry-season discharge (Peru, 1950s–1990s)	Decreased glacier extent in the absence of a clear trend in precipitation	Baraer et al. (2012)
7	Disappearance of Chacaltaya Glacier, Bolivia (2009)	Ascent of freezing isotherm at 50 meters per decade, 1980s–2000s	Rosenzweig et al. (2007)
8	More intense extremes of precipitation (northern tropics and mid-latitudes, 1951–1999)	Anthropogenic greenhouse gas emissions	Min et al. (2011)
9	Fraction of risk of flooding (England and Wales, autumn 2000)	Extreme precipitation attributable to anthropogenic greenhouse radiation	Pall et al. (2011)
10	Decreased recharge of karst aquifers (Spain, 20th century)	Decreased precipitation, and possibly increased temperature; multiple confounding factors	Aguilera and Murillo (2009)
11	Decreased groundwater recharge (Kashmir, 1985–2005)	Decreased winter precipitation	Jeelani (2008)
12	Increased dissolved organic carbon in upland lakes (UK, 1988–2003)	Increased temperature and precipitation; multiple confounding factors	Evans et al. (2005)
13	Increased anoxia in a reservoir, moderated during ENSO (El Niño-Southern Oscillation) episodes (Spain, 1964–1991 and 1994–2007)	Decreased runoff due to decreased precipitation and increased evaporative demand	Marcé et al. (2010)
14	Variable fecal pollution in a saltwater wetland (California, 1969–2000)	Variable storm runoff; 70% of coliform variability attributable to variable precipitation	Pednekar et al. (2005)
15	Nutrient flushing from swamps, reservoirs (North Carolina, 1978–2003)	Hurricanes	Paerl et al. (2006)
16	Increased lake nutrient content (Victoria, Australia, 1984–2000)	Increased air and water temperature	Tibby and Tiller (2007)

of the documented change is not due to natural variability of the water cycle (Chapter 18; WGI AR5 Chapter 10). For robust attribution to climatic change, all the drivers of the hydrological change must be identified, with confidence levels assigned to their contributions. Human contributions such as water withdrawals, land use change, and pollution mean that this is usually difficult. Nevertheless, many hydrological impacts can be attributed confidently to their climatic drivers (Table 3-1). End-to-end attribution, from human climate-altering activities to impacts on freshwater resources, is not attempted in most studies, because it requires experiments with climate models in which the external natural and anthropogenic forcing is "switched off." However, climate models do not currently simulate the water cycle at fine enough resolution for attribution of most catchment-scale hydrological impacts to anthropogenic climate change. Until climate models and impact models become better

integrated, it is necessary to rely heavily on multistep attribution, in which hydrological changes are shown to result from climatic changes that may in turn result partly from human activities.

Extreme hydrological events, such as floods, prompt speculation about whether they are "caused" by climate change. Climate change can indeed alter the probability of a particular event. However, to estimate the alteration reliably it is necessary to quantify uncertainties due to natural variability in the changed and the unchanged climates, and also—because of the need for model simulations—uncertainties due to limited ability to simulate the climate.

The probability or risk of the extreme event can be measured by recording the fraction of events beyond some threshold magnitude. Call this fraction r_{ctrl} in the simulated actual climate and r_{expt} in the simulated climate in which there is no anthropogenic forcing, and suppose there are many paired instances of r_{ctrl} and r_{expt}, with the ratio of risks in each pair given by $F = r_{expt}/r_{ctrl}$. The distribution of risk ratios F describes the likelihood that the climate change has altered the risk. Several thousand pairs of such simulations were run to estimate the risk ratio for the floods in England and Wales in autumn 2000 (Pall et al., 2011). Each pair started from a unique initial state that differed slightly from a common reference state, and was obtained with a seasonal forecast model driven by patterns of attributable warming found beforehand from four climate-model simulations of the 20th century. The forecast model was coupled to a model of basin-scale runoff and channel-scale hydraulics. It is not probable that such exercises will become routine for assessing single-event risks in, for example, the insurance industry, because the necessary amount of computation is so formidable. Nevertheless, the result was compelling: in each of the four sets of simulation pairs, the risk increased greatly on average in the runs forced by anthropogenic greenhouse radiation. In aggregate, the most probable amount of increase was two- to threefold, and at most a few percent of the simulation pairs suggested that anthropogenic forcing actually decreased the risk. This summary is worded carefully: the thousands of simulation pairs were needed for quantifying the uncertainties, which led unavoidably to a spread of likelihoods and thus to statements about uncertainty about risk that are themselves uncertain.

3.2.2. Precipitation, Evapotranspiration, Soil Moisture, Permafrost, and Glaciers

Global trends in precipitation from several different datasets during 1901–2005 are statistically insignificant (Bates et al., 2008; WGI AR5 Chapter 2). According to regional observations, most droughts and extreme rainfall events of the 1990s and 2000s have been the worst since the 1950s (Arndt et al., 2010), and certain trends in total and extreme precipitation amounts are observed (WGI AR5 Chapter 2). Most regional changes in precipitation are attributed either to internal variability of the atmospheric circulation or to global warming (Lambert et al., 2004; Stott et al., 2010). It was estimated that the 20th century anthropogenic forcing contributed significantly to observed changes in global and regional precipitation (Zhang et al., 2007). Changes in snowfall amounts are indeterminate, as for precipitation; however, consistent with observed warming, shorter snowfall seasons are observed over most of the Northern Hemisphere, with snowmelt seasons starting earlier (Takala et al., 2009). In Norway, increased temperature at lower altitudes has reduced the snow water equivalent (Skaugen et al., 2012).

Steady decreases since the 1960s of global and regional actual evapotranspiration and pan evaporation have been attributed to changes in precipitation, diurnal temperature range, aerosol concentration, (net) solar radiation, vapor pressure deficit, and wind speed (Fu et al., 2009; McVicar et al., 2010; Miralles et al., 2011; Wang A. et al., 2011). Regional downward and upward trends in soil moisture content have been calculated for China from 1950 to 2006, where longer, more severe, and more frequent soil moisture droughts have been experienced over 37% of the land area (Wang A. et al., 2011). This is supported by detected increases since the 1960s in dry days and a prolongation of dry periods (Gemmer et al., 2011; Fischer et al., 2013), and can be attributed to increases in warm days and warm periods (Fischer et al., 2011).

Decreases in the extent of permafrost and increases in its average temperature are widely observed, for example, in some regions of the Arctic and Eurasia (WGI AR5 Chapter 4) and the Andes (Rabassa, 2009). Active layer depth and permafrost degradation are closely dependent on soil ice content. In steep terrain, slope stability is highly affected by changes in permafrost (Harris et al., 2009). The release of greenhouse gases (GHGs) due to permafrost degradation can have unprecedented impacts on the climate, but these processes are not yet well represented in global climate models (Grosse et al., 2011). In most parts of the world glaciers are losing mass (Gardner et al., 2013). For example, almost all glaciers in the tropical Andes have been shrinking rapidly since the 1980s (Rabassa, 2009; Rabatel et al., 2013); similarly, Himalayan glaciers are losing mass at present (Bolch et al., 2012).

3.2.3. Streamflow

Detected trends in streamflow are generally consistent with observed regional changes in precipitation and temperature since the 1950s. In Europe, streamflow (1962–2004) decreased in the south and east and generally increased elsewhere (Stahl et al., 2010, 2012), particularly in northern latitudes (Wilson et al., 2010). In North America (1951–2002), increases were observed in the Mississippi basin and decreases in the U.S. Pacific Northwest and southern Atlantic–Gulf regions (Kalra et al., 2008). In China, a decrease in streamflow in the Yellow River (1960–2000) is consistent with a reduction of 12% in summer and autumn precipitation, whereas the Yangtze River shows a small increase in annual streamflow driven by an increase in monsoon rains (Piao et al., 2010; see Table 3-1). These and other streamflow trends must be interpreted with caution (Jones, 2011) because of confounding factors such as land use changes (Zhang and Schilling, 2006), irrigation (Kustu et al., 2010), and urbanization (Wang and Cai, 2010).

In a global analysis of simulated streamflows (1948–2004), about one-third of the top 200 rivers (including the Congo, Mississippi, Yenisei, Paraná, Ganges, Columbia, Uruguay, and Niger) showed significant trends in discharge; 45 recorded decreases and only 19 recorded increases (Dai et al., 2009). Decreasing trends in low and mid-latitudes are consistent with recent drying and warming in West Africa, southern Europe, south and east Asia, eastern Australia, western Canada and the USA, and northern South America (Dai, 2013). The contribution to

observed streamflow changes due to decreased stomatal opening of many plant species at higher carbon dioxide (CO_2) concentration remains disputed (Box CC-VW).

In regions with seasonal snow storage, warming since the 1970s has led to earlier spring discharge maxima (*robust evidence*, *high agreement*) and has increased winter flows because more winter precipitation falls as rain instead of snow (Clow, 2010; Korhonen and Kuusisto, 2010; Tan et al., 2011). There is *robust evidence* of earlier breakup of river ice in Arctic rivers (de Rham et al., 2008; Smith, 2000). Where streamflow is lower in summer, decrease in snow storage has exacerbated summer dryness (Cayan et al., 2001; Knowles et al., 2006).

3.2.4. Groundwater

Attribution of observed changes in groundwater level, storage, or discharge to climatic changes is difficult owing to additional influences of land use changes and groundwater abstractions (Stoll et al., 2011). Observed trends are largely attributable to these additional influences. The extent to which groundwater abstractions have already been affected by climate change is not known. Both detection of changes in groundwater systems and attribution of those changes to climatic changes are rare owing to a lack of appropriate observation wells and a small number of studies. Observed decreases of the discharge of groundwater-fed springs in Kashmir (India) since the 1980s were attributed to observed precipitation decreases (Jeelani, 2008; Table 3-1). A model-based assessment of observed decreases of groundwater levels in four overexploited karst aquifers in Spain led to the conclusion that groundwater recharge not only decreased strongly during the 20th century due to the decreasing precipitation but also that groundwater recharge as a fraction of observed precipitation declined progressively, possibly indicating an increase in evapotranspiration (Aguilera and Murillo, 2009; Table 3-1).

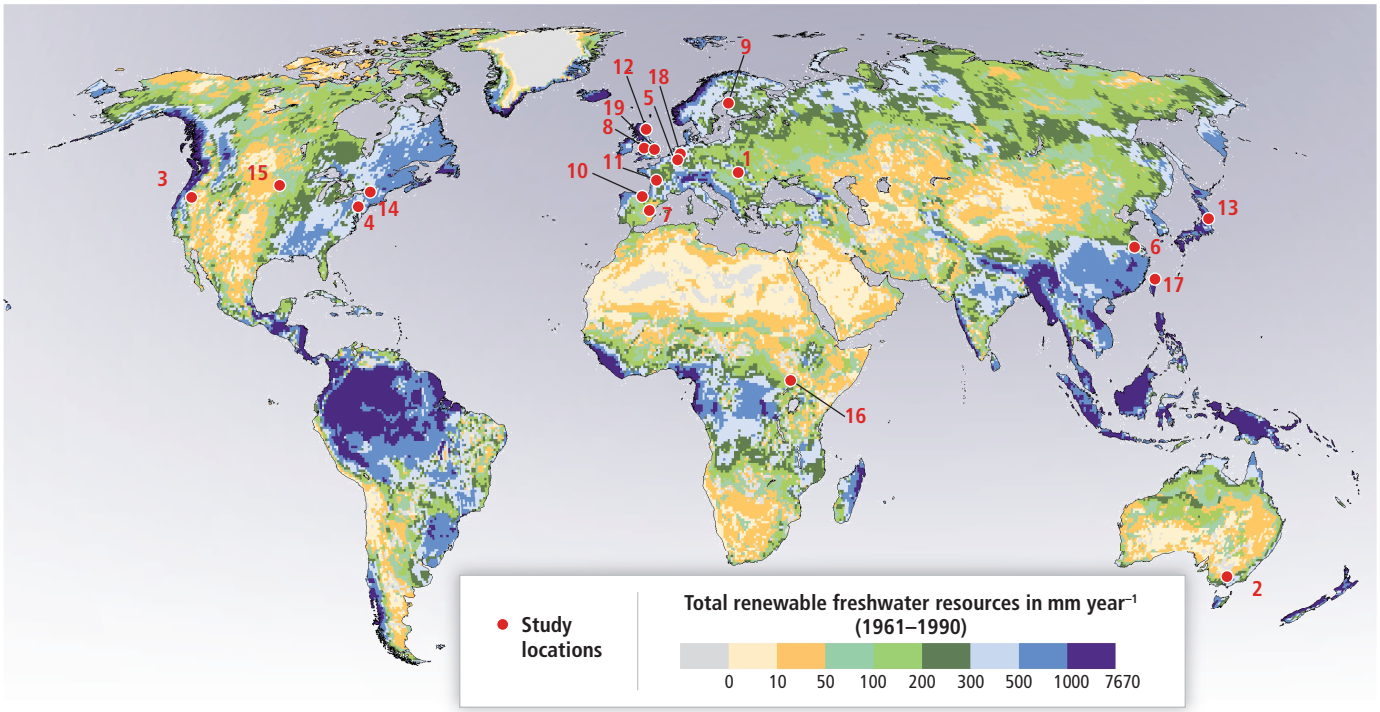
3.2.5. Water Quality

Most observed changes of water quality due to climate change (Table 3-1; Figure 3-2) are known from isolated studies, mostly of rivers or lakes in high-income countries, of a small number of variables. In addition, even though some studies extend over as many as 80 years, most are short term. For lakes and reservoirs, the most frequently reported change is more intense eutrophication and algal blooms at higher temperatures, or shorter hydraulic retention times and higher nutrient loads resulting from increased storm runoff (*medium* to *robust evidence*, *high agreement*). Increased runoff results in greater loads of salts, fecal coliforms, pathogens, and heavy metals (Pednekar et al., 2005; Paerl et al., 2006; Tibby and Tiller, 2007; Boxall et al., 2009) (*robust evidence*, *medium* to *high agreement*, depending on the pollutant). In some cases there are associated impacts on health. For instance, hospital admissions for gastrointestinal illness in elderly people increased by 10% when turbidity increased in the raw water of a drinking water plant even when treated using conventional procedures (Schwartz et al., 2000). However, positive impacts were also reported. For example, the risk of eutrophication was reduced when nutrients were flushed from lakes and estuaries by more frequent storms and hurricanes (Paerl and Huisman, 2008). For rivers, all reported impacts on water quality were negative. Greater runoff, instead of diluting pollution, swept more pollutants from the soil into watercourses (*robust evidence*, *medium* to *high agreement*) (Boxall et al., 2009; Loos et al., 2009; Benítez-Gilabert et al., 2010; Gascuel-Odoux et al., 2010; Howden et al., 2010; Saarinen et al., 2010; Tetzlaff et al., 2010; Macleod et al., 2012). Increased organic matter content impaired the quality of conventionally treated drinking water (Weatherhead and Howden, 2009). In streams in semiarid and arid areas, temperature changes had a stronger influence on the increase of organic matter, nitrates, and phosphorus than precipitation changes (Ozaki et al., 2003; Chang, 2004; Benítez-Gilabert et al., 2010) (*limited evidence*, *medium agreement*). Studies of impacts on groundwater quality are limited and mostly report elevated concentrations of fecal coliforms during the rainy season or after extreme rain events (*medium evidence*, *high agreement*), with varying response times (Curriero et al., 2001; Tumwine et al., 2002, 2003; Auld et al., 2004; Jean et al., 2006; Seidu et al., 2013). Given the widespread use of groundwater for municipal supply and minimal or lacking treatment of drinking water in poor regions, increased pollution is a source of concern (Jean et al., 2006; Seidu et al., 2013). Another concern is the nonlinearity (except for temperature) of relationships between water quality and climatic variables (*limited evidence*, *medium agreement*). In general, the linkages between observed effects on water quality and climate should be interpreted cautiously and at the local level, considering the type of water body, the pollutant of concern, the hydrological regime, and the many other possible sources of pollution (*high confidence*; Senhorst and Zwolsman, 2005; Whitehead et al., 2009a; Benítez-Gilabert et al., 2010; Howden et al., 2010; Kundzewicz and Krysanova, 2010; Ventela et al., 2011).

3.2.6. Soil Erosion and Sediment Load

Precipitation extremes in many regions have increased since 1950 (Seneviratne et al., 2012), which suggests an increase in rainfall erosivity that would enhance soil erosion and stream sediment loads. A warmer climate may affect soil moisture, litter cover, and biomass production and can bring about a shift in winter precipitation from snow to more erosive rainfall (Kundzewicz et al., 2007) or, in semiarid regions, an increase in wildfires with subsequent rainfall leading to intense erosive events (Nyman et al., 2011; Bussi et al., 2013). The effects of climate change on soil erosion and sediment load are frequently obscured by human agricultural and management activities (Walling, 2009).

Only few studies have isolated the contribution of climate change to observed trends in soil erosion and sediment load. In the Yellow River basin, where soil erosion results mostly from heavy rainfall, reduced precipitation (~10%) contributed about 30% to a total reduction in stream sediment loads reaching the sea during 2000–2005, compared to 1950–1968, with the remaining 70% attributable to sediment trapping in reservoirs and soil conservation measures (Wang et al., 2007; Miao et al., 2011). Dai et al. (2008), analyzing the decrease in sediment load of the Yangtze River over 1956–2002, found that climate change was responsible for an increase of about 3 ± 2%; most of the decline in its lower reaches was due to dam construction (Three Gorges Dam) and soil conservation measures.



	Location	Study period	Observation on water quality	Reference
1	Danube River, Bratislava, Slovakia	1926–2005	The water temperature is rising but the trend of the weighted long-term average temperature values resulted close to zero because of the interannual distribution of the mean monthly discharge.	Pekarova et al. (2008)
2	Purrumbete, Colac and Bullen Merri Lakes, Victoria, Australia	1984–2000	The increases in salinity and nutrient content were associated with the air temperature increase; salinity in addition was associated with variations in the effective precipitation.	Tibby and Tiller (2007)
3	Lake Tahoe, California and Nevada States, USA	1970–2007	Thermal stability resulting from a higher ambient temperature decreased the dissolved oxygen content.	Sahoo et al. (2010)
4	Neuse River Estuary, North Carolina, USA	1979–2003	Intense storms and hurricanes flushed nutrients from the estuary, reducing eutrophic conditions and the risk of algal blooms.	Paerl et al., (2006); Paerl and Huisman (2008)
5	River Meuse, western Europe	1976–2003	Increase of water temperature and the content of major elements and some heavy metals were associated with droughts. Algal blooms resulted from a higher nutrient content due to higher water temperature and longer residence time.	van Vliet and Zwolsman (2008)
6	Lake Taihu, Wuxi, Jiangsu, China	2007	The lake, already suffering from periodic cyanobacterial blooms, was affected by a very intensive bloom in May 2007 attributed to an unusually warm spring and leading to the presence of *Microcystis* toxins in the water. This forced two million people to drink bottled water for at least one week.	Qin et al. (2010)
7	Sau Reservoir, Spain	1964–2007	Stream flow variations were of greater significance than temperature increases in the depletion of dissolved oxygen.	Marcé et al. (2010)
8	22 upland waters in UK	1988–2002	Dissolved organic matter increased due to temperature increase but also due to rainfall variations, acid deposition, land use, and CO_2 enrichment.	Evans et al. (2005)
9	Coastal rivers from western Finland	1913–2007	Low pH values are associated with higher rainfall and river discharge in an acid sulfate soil basin.	Saarinen et al. (2010)
		1961–2007	Critical values of dissolved organic carbon is associated with higher rainfall and river discharge.	
10	15 pristine mountain rivers, northern Spain	1973–2005	For a semiarid area, there is a clear relationship between increases in air temperature and a higher nutrient and dissolved organic carbon content.	Benítez-Gilabert et al. (2010)
11	30 coastal rivers and groundwater of western France	1973–2007 (2–6 years)	Interannual variations in the nutrient content associated with air temperature, rainfall, and management practices changes. These effects were not observed in groundwater because of the delay in response time and the depuration of soil on water.	Gascuel-Odoux et al. (2010)
12	Girnock, Scotland	14 months	Higher risks of fecal pollution are clearly related to rainfall during the wet period.	Tetzlaff et al. (2010)
13	27 rivers in Japan	1987–1995	Increases in organic matter and sediment and decreases in the dissolved oxygen content are associated with increases in ambient temperature. Precipitation increases and variations are associated with an increase in the organic matter, sediments, and chemical oxygen demand content in water.	Ozaki et al. (2003)
14	Conestoga River Basin, Pennsylvania, USA	1977–1997	There is a close association between annual loads of total nitrogen and annual precipitation increases.	Chang (2004)
15	USA	1948–1994	Increased rainfall and runoff are associated with site-specific outbreaks of waterborne disease.	Curriero et al. (2001)
16	Northern and eastern Uganda	1999–2001, 2004, 2007	Elevated concentrations of fecal coliforms are observed in groundwater-fed water supplies during the rainy season.	Tumwine et al. (2002, 2003); Taylor et al. (2009)
17	Taiwan, China	1998	The probability of detecting cases of enterovirus infection was greater than 50%, with rainfall rates >31 mm h^{-1}. The higher the rainfall rate, the higher the probability of an enterovirus epidemic.	Jean et al. (2006)
18	Rhine Basin	1980–2001	Nutrient content in rivers followed seasonal variations in precipitation which were also linked to erosion within the basin.	Loos et al. (2009)
19	River Thames, England	1868–2008	Higher nutrient contents were associated to changes in river runoff and land use.	Howden et al. (2010)

Figure 3-2 | Observations of the impacts of climate on water quality.

Potential impacts of climate change on soil erosion and sediment production are of concern in regions with pronounced glacier retreat (Walling, 2009). Glacial rivers are expected to discharge more meltwater, which may increase sediment loads. However, the *limited evidence* is inconclusive for a global diagnosis of sediment load changes; there are both decreasing (e.g., Iceland; Lawler et al., 2003) and increasing trends (Patagonia; Fernandez et al., 2011). So far, there is no clear evidence that the frequency or magnitude of shallow landslides has changed over past decades (Huggel et al., 2012), even in regions with relatively complete event records (e.g., Switzerland; Hilker et al., 2009). Increased landslide impacts (measured by casualties or losses) in south and Southeast Asia, where landslides are triggered predominantly by monsoon and tropical cyclone activity, are largely attributed to population growth leading to increased exposure (Petley, 2012).

In summary, there is *limited evidence* and *low agreement* that anthropogenic climate change has made a significant contribution to soil erosion, sediment loads, and landslides. The available records are limited in space and time, and evidence suggests that, in most cases, the impacts of land use and land cover changes are more significant than those of climate change.

3.2.7. Extreme Hydrological Events and their Impacts

There is *low confidence*, due to *limited evidence*, that anthropogenic climate change has affected the frequency and magnitude of floods at global scale (Kundzewicz et al., 2013). The strength of the evidence is limited mainly by lack of long-term records from unmanaged catchments. Moreover, in the attribution of detected changes it is difficult to distinguish the roles of climate and human activities (Section 3.2.1). However, recent detection of trends in extreme precipitation and discharge in some catchments implies greater risks of flooding at regional scale (*medium confidence*). More locations show increases in heavy precipitation than decreases (Seneviratne et al., 2012). Flood damage costs worldwide have been increasing since the 1970s, although this is partly due to increasing exposure of people and assets (Handmer et al., 2012).

There is no strong evidence for trends in observed flooding in the USA (Hirsch and Ryberg, 2012), Europe (Mudelsee et al., 2003; Stahl et al., 2010; Benito and Machado, 2012; Hannaford and Hall, 2012), South America, and Africa (Conway et al., 2009). However, at smaller spatial scales, an increase in annual maximum discharge has been detected in parts of northwestern Europe (Petrow and Merz, 2009; Giuntoli et al., 2012; Hattermann et al., 2012), while a decrease was observed in southern France (Giuntoli et al., 2012). Flood discharges in the lower Yangtze basin increased over the last 40 years (Jiang et al., 2008; Zhang et al., 2009), and both upward and downward trends were identified in four basins in the northwestern Himalaya (Bhutiyani et al., 2008). In Australia, only 30% of 491 gauge stations showed trends at the 10% significance level, with decreasing magnitudes in southern regions and increasing magnitudes in the northern regions (Ishak et al., 2010). In Arctic rivers dominated by a snowmelt regime, there is no general trend in flood magnitude and frequency (Shiklomanov et al., 2007). In Nordic countries, significant changes since the mid-20th century are mostly toward earlier seasonal flood peaks, but flood magnitudes show contrasting trends, driven by temperature and precipitation, in basins with and without glaciers increasing peaks in the former and decreasing peaks in the latter (Wilson et al., 2010; Dahlke et al., 2012). Significant trends at almost one-fifth of 160 stations in Canada were reported, most of them decreases in snowmelt-flood magnitudes (Cunderlik and Ouarda, 2009). Similar decreases were found for spring and annual maximum flows (Burn et al., 2010).

Attribution has been addressed by Hattermann et al. (2012), who identified parallel trends in precipitation extremes and flooding in Germany, which for the increasing winter floods are explainable in terms of increasing frequency and persistence of circulation patterns favorable to flooding (Petrow et al., 2009). It is *very likely* that the observed intensification of heavy precipitation is largely anthropogenic (Min et al., 2011; see also Section 3.2.1).

Socioeconomic losses from flooding are increasing (*high confidence*), although attribution to anthropogenic climate change is established only seldom (Pall et al., 2011). Reported flood damages (adjusted for inflation) have increased from an average of US$7 billion per year in the 1980s to about US$24 billion per year in 2011 (Kundzewicz et al., 2013). Economic, including insured, flood disaster losses are higher in developed countries, while fatality rates and economic losses expressed as a proportion of gross domestic product are higher in developing countries. Since 1970, the annual number of flood-related deaths has been in the thousands, with more than 95% in developing countries (Handmer et al., 2012). There is *high confidence* (*medium evidence*, *high agreement*) that greater exposure of people and assets, and societal factors related to population and economic growth, contributed to the increased losses (Handmer et al., 2012; Kundzewicz et al., 2013). When damage records are normalized for changes in exposure and vulnerability (Bouwer, 2011), most studies find no contribution of flooding trends to the trend in losses (Barredo, 2009; Hilker et al., 2009; Benito and Machado, 2012), although there are exceptions (Jiang et al., 2005; Chang et al., 2009).

Assessments of observed changes in "drought" depend on the definition of drought (meteorological, agricultural, or hydrological) and the chosen drought index (e.g., consecutive dry days, Standardized Precipitation Index (SPI), Palmer Drought Severity Index (PDSI), Standardized Runoff Index (SRI); see Seneviratne et al., 2012). Meteorological (rainfall) and agricultural (soil moisture) droughts have become more frequent since 1950 (Seneviratne et al., 2012) in some regions, including southern Europe and western Africa, but in others (including the southern USA; Chen et al., 2012) there is no evidence of change in frequency (WGI AR5 Chapter 2).

Very few studies have considered variations over time in hydrological (streamflow) drought, largely because there are few long records from catchments without direct human interventions. A trend was found toward lower summer minimum flows for 1962–2004 in small catchments in southern and Eastern Europe, but there was no clear trend in northern or Western Europe (Stahl et al., 2010). Models can reproduce observed patterns of drought occurrence (e.g., Prudhomme et al., 2011), but as with climate models their outputs can be very divergent. In simulations of drought at the global scale in 1963–2000 with an ensemble of hydrological models, strong correlations were noted between El Niño-

Southern Oscillation (ENSO) events and hydrological droughts, and—particularly in dry regions—low correlations between meteorological and hydrological droughts, which suggests that hydrological droughts cannot necessarily be inferred from rainfall deficits (van Huijgevoort et al., 2013).

3.3. Drivers of Change for Freshwater Resources

3.3.1. Climatic Drivers

Precipitation and potential evaporation are the main climatic drivers controlling freshwater resources. Precipitation is strongly related to atmospheric water vapor content, because saturation specific humidity depends on temperature: warmer air can hold much more water vapor. Temperature has increased in recent decades while surface and tropospheric relative humidity have changed little (WGI AR5 Chapter 2). Among other climatic drivers are atmospheric CO_2, which affects plant transpiration (Box CC-VW), and deposited black carbon and dust, both of which, even in very small concentrations, enhance melting of snow and ice by reducing the surface albedo.

Uncertainty in the climatic drivers is due mainly to internal variability of the atmospheric system, inaccurate modeling of the atmospheric response to external forcing, and the external forcing itself as described by the Representative Concentration Pathways (RCPs; Section 1.1.3). Internal variability and variation between models account for all of the uncertainty in precipitation in the first few decades of the 21st century in Coupled Model Intercomparison Project Phase 3 (CMIP3) projections (Hawkins and Sutton, 2011). The contribution of internal variability diminishes progressively. By no later than mid-century, most of the uncertainty in precipitation is due to discrepancies between models, and divergent scenarios never contribute more than one-third of the uncertainty. In contrast, the uncertainty in temperature (WGI AR5 Chapter 11) is due mostly to divergent scenarios.

CMIP5 simulations of the water cycle during the 21st century (WGI AR5 Chapter 12), with further constraints added here from 20th century observations, can be summarized as follows:

- Surface temperature, which affects the vapor-carrying capacity of the atmosphere and the ratio of snowfall to precipitation, increases non-uniformly (*very high confidence*), probably by about 1.5 times more over land than over ocean.
- Warming is greatest over the Arctic (*very high confidence*), implying latitudinally variable changes in snowmelt and glacier mass budgets.
- Less precipitation falls as snow and snow cover decreases in extent and duration (*high confidence*). In the coldest regions, however, increased winter snowfall outweighs increased summer snowmelt.
- Wet regions and seasons become wetter and dry regions and seasons become drier (*high confidence*), although one observational analysis (Sun et al., 2012) is discordant; moreover the models tend to underestimate observed trends in precipitation (Noake et al., 2012) and its observed sensitivity to temperature (Liu et al., 2012).
- Global mean precipitation increases in a warmer world (*virtually certain*), but with substantial variations, including some decreases, from region to region. Precipitation tends to decrease in subtropical latitudes, particularly in the Mediterranean, Mexico and Central America, and parts of Australia, and to increase elsewhere, notably at high northern latitudes and in India and parts of central Asia (*likely* to *very likely*; WGI AR5 Figure 12-41). However, precipitation changes generally become statistically significant only when temperature rises by at least 1.4°C, and in many regions projected 21st century changes lie within the range of late 20th century natural variability (Mahlstein et al., 2012).
- Changes in evaporation have patterns similar to those of changes in precipitation, with moderate increases almost everywhere, especially at higher northern latitudes (WGI AR5 Figure 12-25). Scenario-dependent decreases of soil moisture are widespread, particularly in central and southern Europe, southwestern North America, Amazonia, and southern Africa (*medium* to *high confidence*; WGI AR5 Figure 12-23; WGI AR5 Section 12.4.5.3).

More intense extreme precipitation events are expected (IPCC, 2012). One proposed reason is the projected increase in specific humidity: intense convective precipitation in short periods (less than 1 hour) tends to "empty" the water vapor from the atmospheric column (Utsumi et al., 2011; Berg et al., 2013). Annual maxima of daily precipitation that are observed to have 20-year return periods in 1986–2005 are projected to have shorter return periods in 2081–2100: about 14 years for RCP2.6, 11 years for RCP4.5, and 6 years for RCP8.5 (Kharin et al., 2013). Unlike annual mean precipitation, for which the simulated sensitivity to warming is typically 1.5 to 2.5% K^{-1}, the 20-year return amount of daily precipitation typically increases at 4 to 10% K^{-1}. Agreement between model-simulated extremes and reanalysis extremes is good in the extratropics but poor in the tropics, where there is *robust evidence* of greater sensitivity (10 ± 4% K^{-1}, O'Gorman, 2012). In spite of the intrinsic uncertainty of sampling infrequent events, variation between models is the dominant contributor to uncertainty. Model-simulated changes in the incidence of meteorological (rainfall) droughts vary widely, so that there is at best *medium confidence* in projections (Seneviratne et al., 2012). Regions where droughts are projected to become longer and more frequent include the Mediterranean, central Europe, central North America, and southern Africa.

3.3.2. Non-Climatic Drivers

In addition to impacts of climate change, the future of freshwater systems will be impacted strongly by demographic, socioeconomic, and technological changes, including lifestyle changes. These change both exposure to hazard and requirements for water resources. A wide range of socioeconomic futures can produce similar climate changes (van Vuuren et al., 2012), meaning that certain projected hydrological changes (Section 3.4) can occur under a wide range of future demographic, social, economic, and ecological conditions. Similarly, the same future socioeconomic conditions can be associated with a range of different climate futures.

Changing land use is expected to affect freshwater systems strongly in the future. For example, increasing urbanization may increase flood hazards and decrease groundwater recharge. Of particular importance for freshwater systems is future agricultural land use, especially irrigation, which accounts for about 90% of global water consumption and severely impacts freshwater availability for humans and ecosystems (Döll, 2009).

Owing mainly to population and economic growth but also to climate change, irrigation may significantly increase in the future. The share of irrigation from groundwater is expected to increase owing to increased variability of surface water supply caused by climate change (Taylor R. et al., 2013a).

3.4. Projected Hydrological Changes

3.4.1. Methodological Developments in Hydrological Impact Assessment

Most recent studies of the potential impact of climate change on hydrological characteristics have used a small number of climate scenarios. An increasing number has used larger ensembles of regional or global models (e.g., Chiew et al., 2009; Gosling et al., 2010; Arnell, 2011; Bae et al., 2011; Jackson et al., 2011; Olsson et al., 2011; Kling et al., 2012; Arnell and Gosling, 2013). Some studies have developed "probability distributions" of future impacts by combining results from multiple climate projections and, sometimes, different emissions scenarios, making different assumptions about the relative weight to give to each scenario (Brekke et al., 2009b; Manning et al., 2009; Christierson et al., 2012; Liu et al., 2013). These studies conclude that the relative weightings given are typically less important in determining the distribution of future impacts than the initial selection of climate models considered. Very few impact studies (Dankers et al., 2013; Hanasaki et al., 2013; Portmann et al., 2013; Schewe et al., 2013) have so far used scenarios based on CMIP5 climate models, and these have used only a small subset.

Most assessments have used a hydrological model with the "delta method" to create scenarios, which applies projected changes in climate derived from a climate model either to an observed baseline or with a stochastic weather generator. Several approaches to the construction of scenarios at the catchment scale have been developed (Fowler et al., 2007), including dynamical downscaling using regional climate models and a variety of statistical approaches (e.g., Fu et al., 2013). Systematic evaluations of different methods have demonstrated that estimated impacts can be very dependent on the approach used to downscale climate model data, and the range in projected change between downscaling approaches can be as large as the range between different climate models (Quintana Segui et al., 2010; Chen J. et al., 2011). An increasing number of studies (e.g., Fowler and Kilsby, 2007; Hagemann et al., 2011; Kling et al., 2012; Teutschbein and Seibert, 2012; Veijalainen et al., 2012; Weiland et al., 2012a) have run hydrological models with bias-corrected input from regional or global climate model output (van Pelt et al., 2009; Piani et al., 2010; Yang et al., 2010), rather than by applying changes to an observed baseline. The range between different bias correction methods can be as large as the range between climate models (Hagemann et al., 2011), although this is not always the case (Chen C. et al., 2011; Muerth et al., 2013). Some studies (e.g., Falloon and Betts, 2006, 2010; Hirabayashi et al., 2008; Nakaegawa et al., 2013) have examined changes in global-scale river runoff as simulated directly by a high-resolution climate model, rather than by an "off-line" hydrological model. Assessments of the ability of climate models directly to simulate current river flow regimes (Falloon et al., 2011; Weiland et al., 2012b) show that performance depends largely on simulated precipitation and is better for large basins, but the *limited evidence* suggests that direct estimates of change are smaller than off-line estimates (Hagemann et al., 2013).

The effects of hydrological model parameter uncertainty on simulated runoff changes are typically small when compared with the range from a large number of climate scenarios (Steele-Dunne et al., 2008; Cloke et al., 2010; Vaze et al., 2010; Arnell, 2011; Lawrence and Haddeland, 2011). However, the effects of hydrological model structural uncertainty on projected changes can be substantial (Dankers et al., 2013; Hagemann et al., 2013; Schewe et al., 2013), owing to differences in the representation of evaporation and snowmelt processes. In some regions (e.g., high latitudes; Hagemann et al., 2013) with reductions in precipitation (Schewe et al., 2013), hydrological model uncertainty can be greater than climate model uncertainty—although this is based on small numbers of climate models. Much of the difference in projected changes in evaporation is due to the use of different empirical formulations (Milly and Dunne, 2011). In a study in southeast Australia, the effects of hydrological model uncertainty were small compared with climate model uncertainty, but all the hydrological models used the same potential evaporation data (Teng et al., 2012).

Among other approaches to impact assessment, an inverse technique (Cunderlik and Simonovic, 2007) starts by identifying the hydrological changes that would be critical for a system and then uses a hydrological model to determine the meteorological conditions that trigger those changes; the future likelihood of these conditions is estimated by inspecting climate model output, as in a catchment study in Turkey (Fujihara et al., 2008a,b). Another approach constructs response surfaces relating sensitivity of a hydrological indicator to changes in climate. Several studies have used a water-energy balance framework (based on Budyko's hypothesis and formula) to characterize the sensitivity of average annual runoff to changes in precipitation and evaporation (Donohue et al., 2011; Renner and Bernhofer, 2012; Renner et al., 2012). A response surface showing change in flood magnitudes was constructed by running a hydrological model with systematically varying changes in climate (Prudhomme et al., 2010). This approach shows the sensitivity of a system to change, and also allows rapid assessment of impacts under specific climate scenarios which can be plotted on the response surface.

3.4.2. Evapotranspiration, Soil Moisture, and Permafrost

Based on global and regional climate models as well as physical principles, potential evapotranspiration over most land areas is *very likely* to increase in a warmer climate, thereby accelerating the hydrologic cycle (WGI AR5 Chapter 12). Long-term projections of actual evapotranspiration are uncertain in both magnitude and sign. They are affected not only by rising temperatures but also by changing net radiation and soil moisture, decreases in bulk canopy conductance associated with rising CO_2 concentrations, and vegetation changes related to climate change (Box CC-VW; Katul and Novick, 2009). Projections of the response of potential evapotranspiration to a warming climate are also uncertain. Based on six different methodologies, an increase in potential evapotranspiration was associated with global warming (Kingston et al., 2009). Regionally, increases are projected in southern Europe, Central America, southern Africa, and Siberia (Seneviratne et al., 2010). The accompanying decrease in soil moisture increases the

Box 3-1 | Case Study: Himalayan Glaciers

The total freshwater resource in the Himalayan glaciers of Bhutan, China, India, Nepal, and Pakistan is known only roughly; estimates range from 2100 to 5800 Gt (Bolch et al., 2012). Their mass budgets have been negative on average for the past 5 decades. The loss rate may have become greater after about 1995, but it has not been greater in the Himalaya than elsewhere. A recent large-scale measurement, highlighted in Figure 3-3, is the first well-resolved, region-wide measurement of any component of the Himalayan water balance. It suggests strongly that the conventional measurements, mostly on small, accessible glaciers, are not regionally representative.

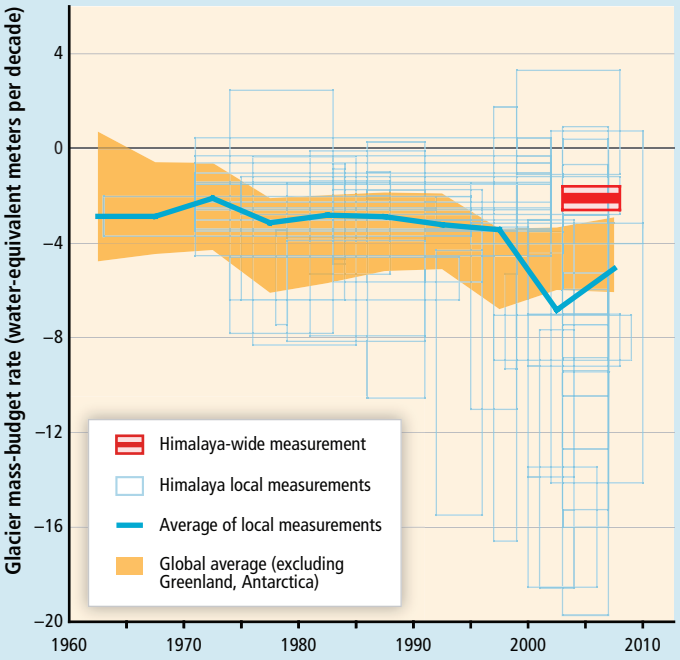


Figure 3-3 | All published glacier mass balance measurements from the Himalaya (based on Bolch et al., 2012). To emphasize the variability of the raw information, each measurement is shown as a box of height ±1 standard deviation centred on the average balance (±1 standard error for multiannual measurements). Region-wide measurement (Kääb et al., 2012) was by satellite laser altimetry. Global average (WGI AR5 Chapter 4) is shown as a 1-sigma confidence region.

Glacier mass changes for 2006–2100 were projected by simulating the response of a glacier model to CMIP5 projections from 14 General Circulation Models (GCMs) (Radić et al., 2013). Results for the Himalaya range between 2% gain and 29% loss to 2035; to 2100, the range of losses is 15 to 78% under RCP4.5. The model-mean loss to 2100 is 45% under RCP4.5 and 68% under RCP8.5 (*medium confidence*). It is *virtually certain* that these projections are more reliable than an earlier erroneous assessment (Cruz et al., 2007) of complete disappearance by 2035.

At the catchment scale, projections do not yet present a detailed region-wide picture. However the GCM-forced simulations of Immerzeel et al. (2013) in Kashmir and eastern Nepal show runoff increasing throughout the century. Peak ice meltwater is reached in mid- to late-century, but increased precipitation overcompensates for the loss of ice.

The growing atmospheric burden of anthropogenic black carbon implies reduced glacier albedo, and measurements in eastern Nepal by Yasunari et al. (2010) suggest that this could yield 70 to 200 mm yr^{-1} of additional meltwater. Deposited soot may outweigh the greenhouse effect as a radiative forcing agent for snowmelt (Qian et al., 2011).

The hazard due to moraine-dammed ice-marginal lakes continues to increase. In the western Himalaya, they are small and stable in size, while in Nepal and Bhutan they are more numerous and larger, and most are growing (Gardelle et al., 2011). There has been little progress on the predictability of dam failure but, of five dams that have failed since 1980, all had frontal slopes steeper than 10° before failure and much gentler slopes afterward (Fujita et al., 2013). This is a promising tool for evaluating the hazard in detail.

The relative importance of Himalayan glacier meltwater decreases downstream, being greatest where the runoff enters dry regions in the west and becoming negligible in the monsoon-dominated east (Kaser et al., 2010). In the mountains, however, dependence on and vulnerability to glacier meltwater are of serious concern when measured per head of population.

risk of extreme hot days (Seneviratne et al., 2006; Hirschi et al., 2011) and heat waves. For a range of scenarios, soil moisture droughts lasting 4 to 6 months double in extent and frequency, and droughts longer than 12 months become three times more common, between the mid-20th century and the end of the 21st century (Sheffield and Wood, 2008). Because of strong natural variability, the generally monotonic projected increases are statistically indistinguishable from the current climate.

Changes consistent with warming are also evident in the freshwater systems and permafrost of northern regions. The area of permafrost is projected to continue to decline over the first half of the 21st century in all emissions scenarios (WGI AR5 Figure 4-18). Under RCP2.6, the permafrost area is projected to stabilize at near 37% less than the 20th century area.

3.4.3. Glaciers

All projections for the 21st century (WGI AR5 Chapter 13) show continued mass loss from glaciers. In glacierized catchments, runoff reaches an annual maximum in summer. As the glaciers shrink, their relative contribution decreases and the annual runoff peak shifts toward spring (e.g., Huss, 2011). This shift is expected with *very high confidence* in most regions, although not, for example, in the eastern Himalaya, where the monsoon and the melt season coincide. The relative importance of high-summer glacier meltwater can be substantial, for example contributing 25% of August discharge in basins draining the European Alps, with area about 105 km^2 and only 1% glacier cover (Huss, 2011). Glacier meltwater also increases in importance during droughts and heat waves (Koboltschnig et al., 2007).

If the warming rate is constant, and if, as expected, ice melting per unit area increases and total ice-covered area decreases, the total annual yield passes through a broad maximum: "peak meltwater." Peak-meltwater dates have been projected between 2010 and 2050 (parts of China, Xie et al., 2006); 2010–2040 (European Alps, Huss, 2011); and mid- to late-century (glaciers in Norway and Iceland, Jóhannesson et al., 2012). Note that the peak can be dated only relative to a specified reference date. Declining yields relative to various dates in the past have been detected in some observational studies (Table 3-1); that is, a peak has been passed already. There is *medium confidence* that the peak response to 20th- and 21st-century warming will fall within the 21st century in many inhabited glacierized basins, where at present society is benefitting from a transitory "meltwater dividend." Variable forcing leads to complex variations of both the melting rate and the extent of ice, which depend on each other.

If they are in equilibrium, glaciers reduce the interannual variability of water resources by storing water during cold or wet years and releasing it during warm years (Viviroli et al., 2011). As glaciers shrink, however, their diminishing influence may make the water supply less dependable.

3.4.4. Runoff and Streamflow

Many of the spatial gaps identified in AR4 have been filled to a very large extent by catchment-scale studies of the potential impacts of climate change on streamflow. The projected impacts in a catchment depend on the sensitivity of the catchment to change in climatic characteristics and on the projected change in the magnitude and seasonal distribution of precipitation, temperature, and evaporation. Catchment sensitivity is largely a function of the ratio of runoff to precipitation: the smaller the ratio, the greater the sensitivity. Proportional changes in average annual runoff are typically between one and three times as large as proportional changes in average annual precipitation (Tang and Lettenmaier, 2012).

Projected scenario-dependent changes in runoff at the global scale, mostly from CMIP3 simulations, exhibit a number of consistent patterns (e.g., Hirabayashi et al., 2008; Döll and Zhang, 2010; Fung et al., 2011; Murray et al., 2012; Okazaki et al., 2012; Tang and Lettenmaier, 2012; Weiland et al., 2012a; Arnell and Gosling, 2013; Nakaegawa et al., 2013; Schewe et al., 2013). Average annual runoff is projected to increase at high latitudes and in the wet tropics, and to decrease in most dry tropical regions. However, for some regions there is very considerable uncertainty in the magnitude and direction of change, specifically in China, south Asia, and large parts of South America. Both the patterns of change and the uncertainty are driven largely by projected changes in precipitation, particularly across south Asia. Figure 3-4 shows the average percentage change in average annual runoff for an increase in global average temperature of 2°C above the 1980–2010 mean, averaged across five CMIP5 climate models and 11 hydrological models. The pattern of change in Figure 3-4 is different in some regions from the pattern shown in WGI AR5 Figure 12-24, largely because it is based on fewer climate models.

The seasonal distribution of change in streamflow varies primarily with the seasonal distribution of change in precipitation, which in turn varies between scenarios. Figure 3-5 illustrates this variability, showing the percentage change in monthly average runoff in a set of catchments from different regions using scenarios from seven climate models, all scaled to represent a 2°C increase in global mean temperature above the 1961–1990 mean. One of the climate models is separately highlighted, and for that model the figure also shows changes with a 4°C rise in temperature. In the Mitano catchment in Uganda, for example, there is a nonlinear relationship between amount of climate change and hydrological response. Incorporating uncertainty in hydrological model structure (Section 3.4.1) would increase further the range in projected impacts at the catchment scale.

There is a much more consistent pattern of future seasonal change in areas currently influenced by snowfall and snowmelt. A global analysis (Adam et al., 2009) with multiple climate scenarios shows a consistent shift to earlier peak flows, except in some regions where increases in precipitation are sufficient to result in increased, rather than decreased, snow accumulation during winter. The greatest changes are found near the boundaries of regions that currently experience considerable snowfall, where the marginal effect of higher temperatures on snowfall and snowmelt is greatest.

3.4.5. Groundwater

While the relation between groundwater and climate change was rarely investigated before 2007, the number of studies and review papers

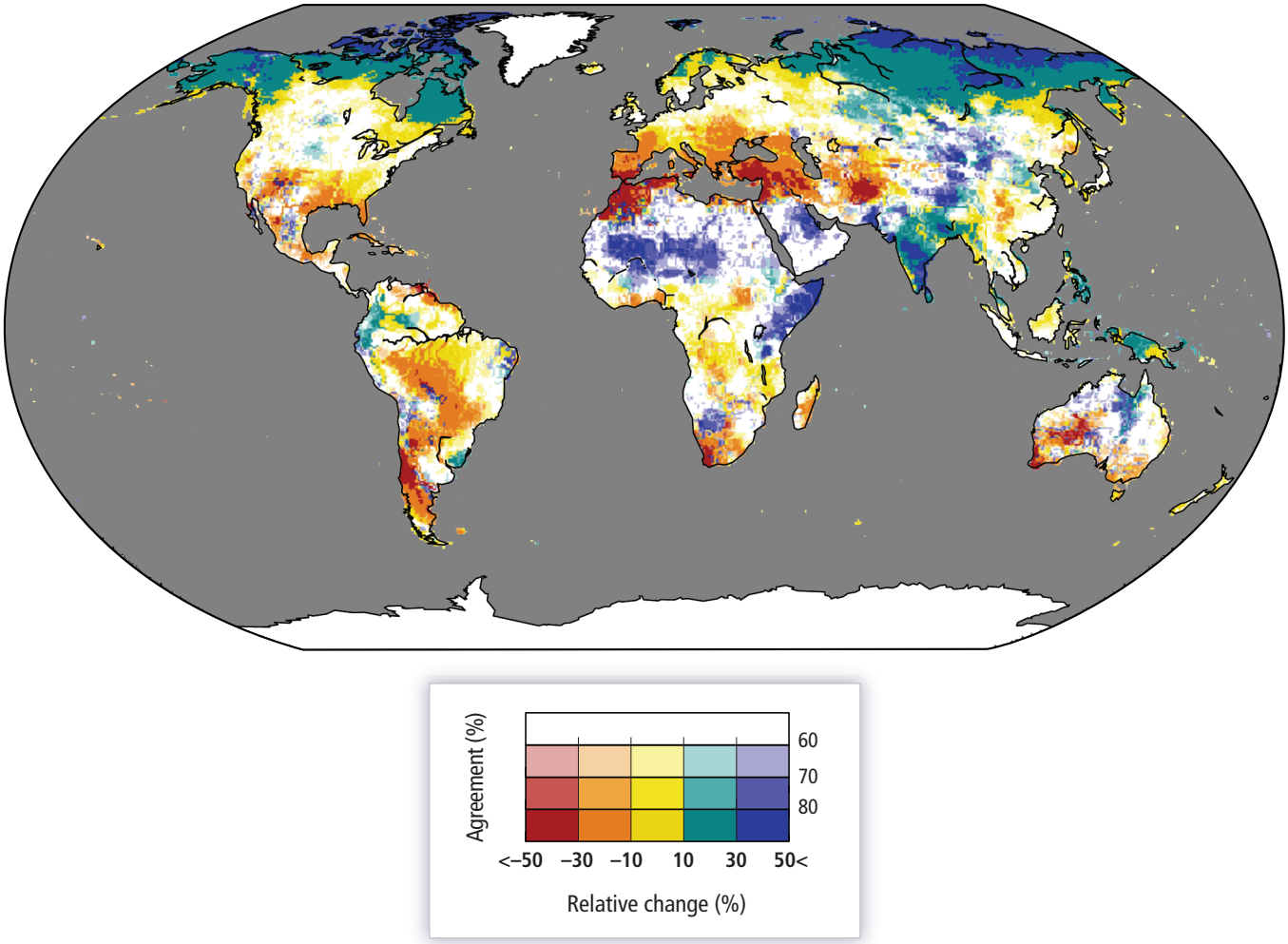


Figure 3-4 | Percentage change of mean annual streamflow for a global mean temperature rise of 2°C above 1980–2010 (2.7°C above pre-industrial). Color hues show the multi-model mean change across 5 General Circulation Models (GCMs) and 11 Global Hydrological Models (GHMs), and saturation shows the agreement on the sign of change across all 55 GHM–GCM combinations (percentage of model runs agreeing on the sign of change) (Schewe et al., 2013).

(Green et al., 2011; Taylor R. et al., 2013a) has increased significantly since then. Ensemble studies, relying on between 4 and 20 climate models, of the impact of climate change on groundwater recharge and partially also on groundwater levels were done for the globe (Portmann et al., 2013), all of Australia (Crosbie et al., 2013a), the German Danube basin (Barthel et al., 2010), aquifers in Belgium and England (Goderniaux et al., 2011; Jackson et al., 2011), the Pacific coast of the USA and Canada (Allen et al., 2010), and the semiarid High Plains aquifer of the USA (Ng et al., 2010; Crosbie et al., 2013b). With three exceptions, simulations were run under only one GHG emissions scenario. The range over the climate models of projected groundwater changes was large, from significant decreases to significant increases for the individual study areas, and the range of percentage changes of projected groundwater recharge mostly exceeded the range of projected precipitation changes. The uncertainties in projected groundwater recharge that originate in the hydrological models have not yet been explored. There are only a few studies of the impacts on groundwater of vegetation changes in response to climate change and CO_2 increase (Box CC-VW). Nor are there any studies on the impact of climate-driven changes of land use on groundwater recharge, even though projected increases in precipitation and streamflow variability due to climate change are expected to lead to increased groundwater abstraction (Taylor R. et al., 2013a), lowering groundwater levels and storage.

Under any particular climate scenario, the areas where total runoff (sum of surface runoff and groundwater recharge) is projected to increase (or decrease) roughly coincide with the areas where groundwater recharge and thus renewable groundwater resources are projected to increase (or decrease) (Kundzewicz and Döll, 2009). Changes in precipitation intensity affect the fraction of total runoff that recharges groundwater. Increased precipitation intensity may decrease groundwater recharge owing to exceedance of the infiltration capacity (typically in humid areas), or may increase it owing to faster percolation through the root zone and thus reduced evapotranspiration (typically in semiarid areas) (Liu, 2011; Taylor R. et al., 2013b). The sensitivity of groundwater recharge and levels to climate change is diminished by perennial vegetation, fine-grained soils, and aquitards and is enhanced by annual cropping, sandy soils, and unconfined (water table) aquifers (van Roosmalen et al., 2007; Crosbie et al., 2013b). The sensitivity of groundwater recharge change to precipitation change was found to be highest for low groundwater

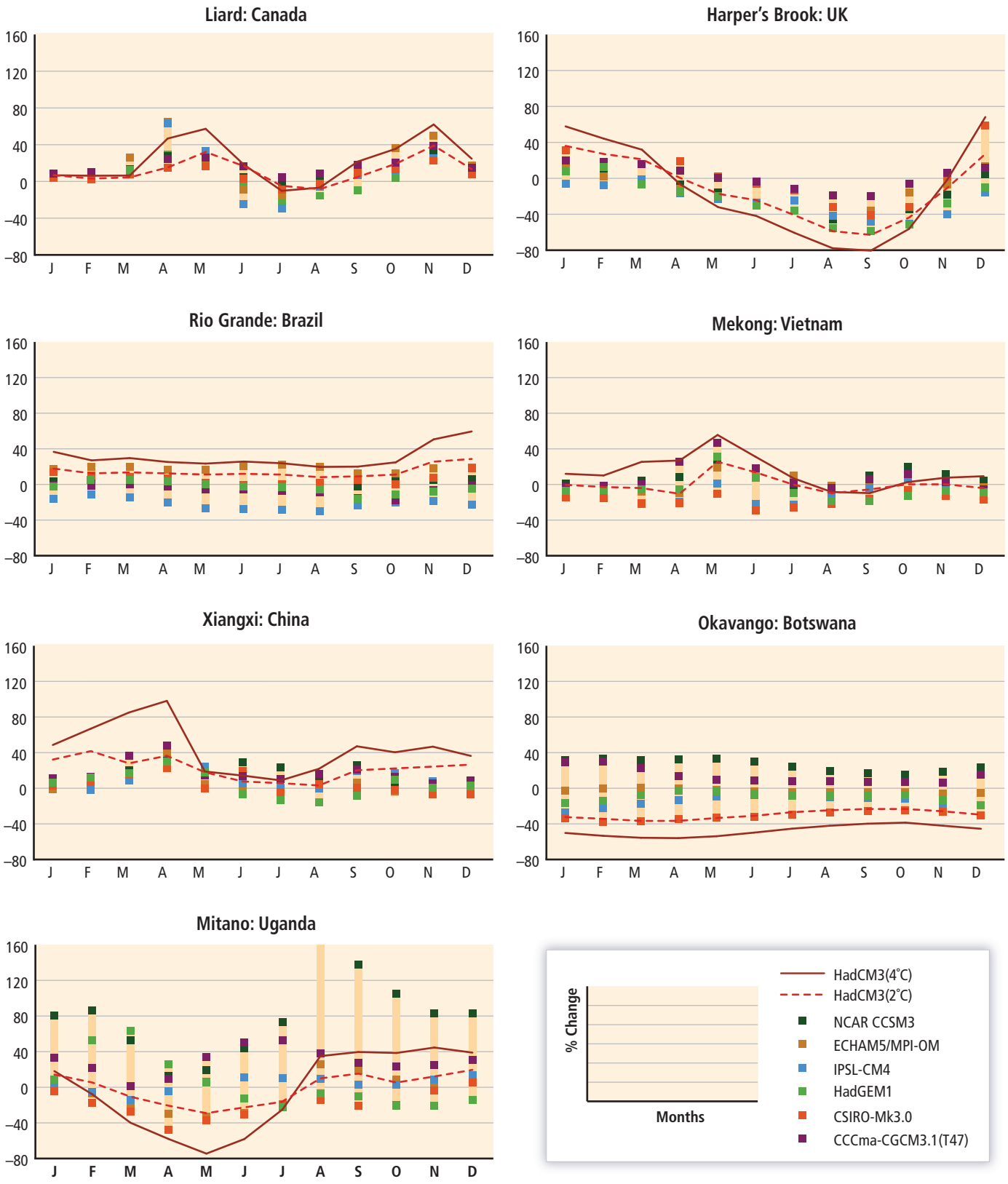


Figure 3-5 | Change in mean monthly runoff across seven climate models in seven catchments, with a 2°C increase in global mean temperature above 1961–1990 (Kingston and Taylor, 2010; Arnell, 2011; Hughes et al., 2011; Kingston et al., 2011; Nobrega et al., 2011; Thorne, 2011; Xu et al., 2011). One of the seven climate models (HadCM3) is highlighted separately, showing changes with both a 2°C increase (dotted line) and a 4°C increase (solid line).

recharge and lowest for high groundwater recharge, the ratio of recharge change to precipitation change ranging from 1.5 to 6.0 in the semiarid High Plains aquifer (Crosbie et al., 2013b). Decreasing snowfall may lead to lower groundwater recharge even if precipitation remains constant; at sites in the southwestern USA, snowmelt provides at least 40 to 70% of groundwater recharge, although only 25 to 50% of average annual precipitation falls as snow (Earman et al., 2006).

Climate change affects coastal groundwater not only through changes in groundwater recharge but also through sea level rise which, together with the rate of groundwater pumping, determines the location of the saltwater/freshwater interface. Although most confined aquifers are expected to be unaffected by sea level rise, unconfined aquifers are expected to suffer from saltwater intrusion (Werner et al., 2012). The volume available for freshwater storage is reduced if the water table cannot rise freely as the sea level rises (Masterson and Garabedian, 2007; Werner et al., 2012). This happens where land surfaces are low lying, for example, on many coral islands and in deltas, but also where groundwater discharges to streams. If the difference between the groundwater table and sea level is decreased by 1 m, the thickness of the unconfined freshwater layer decreases by roughly 40 m (Ghyben-Herzberg relation). Deltas are also affected by storm surges that drive saltwater into stream channels, contaminating the underlying fresh groundwater from above (Masterson and Garabedian, 2007). In three modeling studies, the impact of sea level rise on groundwater levels was found to be restricted to areas within 10 km from the coast (Carneiro et al., 2010; Oude Essink et al., 2010; Yechieli et al., 2010). Saltwater intrusion due to sea level rise is mostly a very slow process that may take several centuries to reach equilibrium (Webb and Howard, 2011). Even small rates of groundwater pumping from coastal aquifers are expected to lead to stronger salinization of the groundwater than sea level rise during the 21st century (Ferguson and Gleeson, 2012; Loaiciga et al., 2012).

Changes in groundwater recharge also affect streamflow. In the Mitano basin in Uganda, mean global temperature increases of 4°C or more with respect to 1961–1990 are projected to decrease groundwater outflow to the river so much that the spring discharge peak disappears and the river flow regime changes from bimodal to unimodal (one seasonal peak only) (Kingston and Taylor, 2010; Figure 3-5). Changing groundwater tables affect land surface energy fluxes, including evaporation, and thus feed back on the climate system, in particular in semiarid areas where the groundwater table is within 2 to 10 m of the surface (Jiang et al., 2009; Ferguson and Maxwell, 2010).

3.4.6. Water Quality

Climate change affects the quality of water through a complex set of natural and anthropogenic mechanisms working concurrently in parallel and in series. Projections under climate change scenarios are difficult, both to perform and interpret, because they require not only integration of the climate models with those used to analyze the transportation and transformation of pollutants in water, soil, and air but also the establishment of a proper baseline (Arheimer et al., 2005; Andersen et al., 2006; Wilby et al., 2006; Ducharne, 2008; Marshall and Randhir, 2008; Bonte and Zwolsman, 2010; Towler et al., 2010; Trolle et al., 2011; Rehana and Mujumdar, 2012). The models have different spatial scales and have to be adapted and calibrated to local conditions for which adequate and appropriate information is needed. In consequence, there are few projections of the impacts of climate change on water quality; where available, their uncertainty is high. It is evident, however, that water quality projections depend strongly on (1) local conditions; (2) climatic and environmental assumptions; and (3) the current or reference pollution state (Chang, 2004; Whitehead et al., 2009a,b; Bonte and Zwolsman, 2010; Kundzewicz and Krysanova, 2010; Sahoo et al., 2010; Trolle et al., 2011). Most projections suggest that future negative impacts will be similar in kind to those already observed in response to change and variability in air and water temperature, precipitation, and storm runoff, and to many confounding anthropogenic factors (Chang, 2004; Whitehead et al., 2009a). This holds for natural and artificial reservoirs (Brikowski, 2008; Ducharne, 2008; Marshall and Randhir, 2008; Loos et al., 2009; Bonte and Zwolsman, 2010; Qin et al., 2010; Sahoo et al., 2010; Trolle et al., 2011), rivers (Andersen et al., 2006; Whitehead et al., 2009a,b; Bowes et al., 2012) and groundwater (Butscher and Huggenberger, 2009; Rozemeijer et al., 2009).

3.4.7. Soil Erosion and Sediment Load

Heavy rainfalls are *likely* to become more intense and frequent during the 21st century in many parts of the world (Seneviratne et al., 2012; WGI AR5 Chapter 11), which may lead to more intense soil erosion even if the total rainfall does not increase. At the global scale, soil erosion simulated assuming doubled CO_2 is projected to increase about 14% by the 2090s, compared to the 1980s (9% attributed to climate change and 5% to land use change), with increases by as much as 40 to 50% in Australia and Africa (Yang et al., 2003). The largest increases are expected in semiarid areas, where extreme events may contribute about half of total erosion; for instance, in Mediterranean Spain 43% of sediment yield over the time period 1990–2009 was produced by a single event (Bussi et al., 2013). In agricultural lands in temperate regions, soil erosion may respond to more intense erosion in complex nonlinear ways; for instance in the UK a 10% increase in winter rainfall (i.e., during early growing season) could increase annual erosion of arable land by up to 150% (Favis-Mortlock and Boardman, 1995), while in Austria a simulation for 2070–2099 projected a decrease of rainfall by 10 to 14% in erosion-sensitive months and thus a decline in soil erosion by 11 to 24% (Scholz et al., 2008). Land management practices are critical for mitigating soil erosion under projected climate change. In China's Loess Plateau, four GCMs coupled to an erosion model show soil erosion increasing by –5 to 195% of soil loss during 2010–2039 under conventional tillage, for three emission scenarios (*Special Report on Emission Scenarios* (SRES) A2 and B2, and IS92a), whereas under conservation tillage they show decreases of 26 to 77% (Li et al., 2011).

Climate change will also affect the sediment load in rivers by altering water discharge and land cover. For example, an increase in water discharge of 11 to 14% in two Danish rivers under the SRES A2 emission scenario was projected to increase the annual suspended sediment load by 9 to 36% during 2071–2100 (Thodsen et al., 2008). Increases in total precipitation, increased runoff from glaciers, permafrost degradation, and the shift of precipitation from snow to rain will further increase soil erosion and sediment loads in colder regions (Lu et al., 2010). In a major

Frequently Asked Questions

FAQ 3.1 | How will climate change affect the frequency and severity of floods and droughts?

Climate change is projected to alter the frequency and magnitude of both floods and droughts. The impact is expected to vary from region to region. The few available studies suggest that flood hazards will increase over more than half of the globe, in particular in central and eastern Siberia, parts of Southeast Asia including India, tropical Africa, and northern South America, but decreases are projected in parts of northern and Eastern Europe, Anatolia, central and East Asia, central North America, and southern South America (*limited evidence*, *high agreement*).The frequency of floods in small river basins is *very likely* to increase, but that may not be true of larger watersheds because intense rain is usually confined to more limited areas. Spring snowmelt floods are *likely* to become smaller, both because less winter precipitation will fall as snow and because more snow will melt during thaws over the course of the entire winter. Worldwide, the damage from floods will increase because more people and more assets will be in harm's way.

By the end of the 21st century meteorological droughts (less rainfall) and agricultural droughts (drier soil) are projected to become longer, or more frequent, or both, in some regions and some seasons, because of reduced rainfall or increased evaporation or both. But it is still uncertain what these rainfall and soil moisture deficits might mean for prolonged reductions of streamflow and lake and groundwater levels. Droughts are projected to intensify in southern Europe and the Mediterranean region, central Europe, central and southern North America, Central America, northeast Brazil, and southern Africa. In dry regions, more intense droughts will stress water supply systems. In wetter regions, more intense seasonal droughts can be managed by current water supply systems and by adaptation; for example, demand can be reduced by using water more efficiently, or supply can be increased by increasing the storage capacity in reservoirs.

headwater basin of the Ganges River, increased precipitation and glacier runoff are projected to increase sediment yield by 26% by 2050 (Neupane and White, 2010). In the tropics, the intensity of cyclones is projected to increase 2 to 11% by 2100, which may increase soil erosion and landslides (Knutson et al., 2010).

In summary, projected increases in heavy rainfall and temperature will lead to changes in soil erosion and sediment load, but owing to the nonlinear dependence of soil erosion on rainfall rate and its strong dependence on land cover there is *low confidence* in projected changes in erosion rates. At the end of the 21st century, the impact of climate change on soil erosion is expected to be twice the impact of land use change (Yang et al., 2003), although management practices may mitigate the problem at catchment scale.

3.4.8. Extreme Hydrological Events (Floods and Droughts)

The *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX; Seneviratne et al., 2012) recognized that projected increases in temperature and heavy precipitation imply regional-scale changes in flood frequency and intensity, but with *low confidence* because these projections were obtained from a single GCM. Global flood projections based on multiple CMIP5 GCM simulations coupled with global hydrology and land surface models (Dankers et al., 2013; Hirabayashi et al., 2013) show flood hazards increasing over about half of the globe, but with great variability at the catchment scale. Projections of increased flood hazard are consistent for parts of south and Southeast Asia, tropical Africa, northeast Eurasia, and South America (Figure 3-6), while decreases are projected in parts of northern and Eastern Europe, Anatolia, central Asia, central North America, and southern South America. This spatial pattern resembles closely that described by Seneviratne et al. (2012), but the latest projections justify *medium confidence* despite new appreciation of the large uncertainty owing to variation between climate models and their coupling to hydrological models.

There have been several assessments of the potential effect of climate change on meteorological droughts (less rainfall) and agricultural droughts (drier soil) (e.g., WGI AR5 Chapter 12; Vidal et al., 2012; Orlowsky and Seneviratne, 2013), but few on hydrological droughts, either in terms of river runoff or groundwater levels. Many catchment-scale studies (Section 3.4.4) consider changes in indicators of low river flow (such as the flow exceeded 95% of the time), but these indicators do not necessarily characterize "drought" as they define neither duration nor spatial extent, and are not necessarily particularly extreme or rare. In an ensemble comparison under SRES A1B of the proportion of the land surface exhibiting significant projected changes in hydrological drought frequency to the proportions exhibiting significant changes in meteorological and agricultural drought frequency, 18 to 30% of the land surface (excluding cold areas) experienced a significant increase in the frequency of 3-month hydrological droughts, while about 15 to 45% saw a decrease (Taylor I. et al., 2013). This is a smaller area with increased frequency, and a larger area with decreased frequency, than for meteorological and agricultural droughts, and is understandable because river flows reflect the accumulation of rainfall over time. Flows during dry periods may be sustained by earlier rainfall. For example, at the catchment scale in the Pacific Northwest (Jung and Chang, 2012),

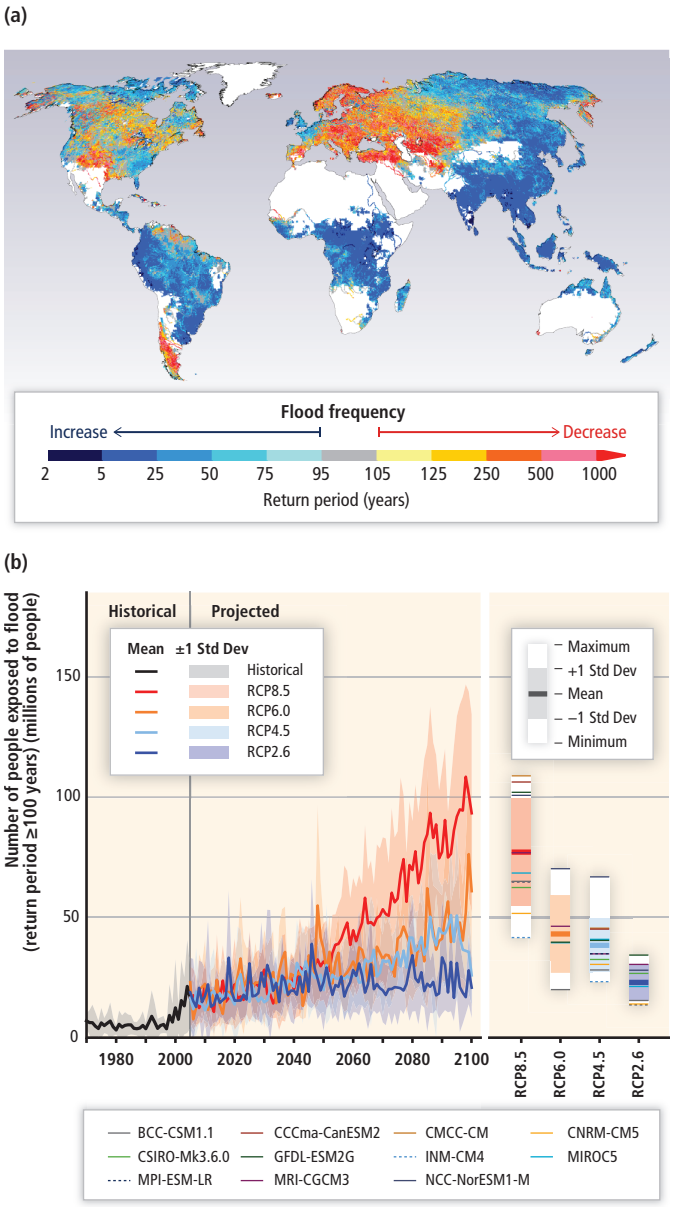


Figure 3-6 | (a) Multi-model median return period (years) in the 2080s for the 20th century 100-year flood (Hirabayashi et al., 2013), based on one hydrological model driven by 11 Coupled Model Intercomparison Project Phase 5 (CMIP5) General Circulation Models (GCMs) under Representative Concentration Pathway 8.5 (RCP8.5). At each location the magnitude of the 100-year flood was estimated by fitting a Gumbel distribution function to time series of simulated annual maximum daily discharge in 1971–2000, and the return period of that flood in 2071–2100 was estimated by fitting the same distribution to discharges simulated for that period. Regions with mean runoff less than 0.01 mm day^{-1}, Antarctica, Greenland, and Small Islands are excluded from the analysis and indicated in white. (b) Global exposure to the 20th-century 100-year flood (or greater) in millions of people (Hirabayashi et al., 2013). Left: Ensemble means of historical (black thick line) and future simulations (colored thick lines) for each scenario. Shading denotes ±1 standard deviation. Right: Maximum and minimum (extent of white), mean (thick colored lines), ±1 standard deviation (extent of shading), and projections of each GCM (thin colored lines) averaged over the 21st century. The impact of 21st century climate change is emphasized by fixing the population to that of 2005. Annual global flood exposure increases over the century by 4 to 14 times as compared to the 20th century (4 ± 3 (RCP2.6), 7 ± 5 (RCP4.5), 7 ± 6 (RCP6.0), and 14 ± 10 (RCP8.5) times, or 0.1% to 0.4 to 1.2% of the global population in 2005). Under a scenario of moderate population growth (UN, 2011), the global number of exposed people is projected to increase by a factor of 7 to 25, depending on the RCP, with strong increases in Asia and Africa due to high population growth.

short hydrological droughts are projected to increase in frequency while longer droughts remain unchanged because, although dry spells last longer, winter rainfall increases.

The impacts of floods and droughts are projected to increase even when the hazard remains constant, owing to increased exposure and vulnerability (Kundzewicz et al., 2013). Projected flood damages vary greatly between models and from region to region, with the largest losses in Asia. Studies of projected flood damages are mainly focused in Europe, the USA, and Australia (Handmer et al., 2012; Bouwer, 2013). In Europe, the annual damage (€6.4 billion) and number of people exposed (200,000) in 1961–1990 are expected to increase about twofold by the 2080s under scenario B2 and about three times under scenario A2 (Feyen et al., 2012). Drought impacts at continental and smaller scales are difficult to assess because they will vary greatly with the local hydrological setting and water management practices (Handmer et al., 2012). More frequent droughts due to climate change may challenge existing water management systems (Kim et al., 2009); together with an increase of population, this may place at risk even the domestic supply in parts of Africa (MacDonald et al., 2009).

3.5. Projected Impacts, Vulnerabilities, and Risks

In general, projections of freshwater-related impacts, vulnerabilities, and risks caused by climate change are evaluated by comparison to historical conditions. Such projections are helpful for understanding human impact on nature and for supporting adaptation to climate change. However, for supporting decisions on climate mitigation, it is more helpful to compare the different hydrological changes that are projected under different future GHG emissions scenarios, or different amounts of global mean temperature rise. One objective of such projections is to quantify what may happen under current water resources management practice, and another is to indicate what actions may be needed to avoid undesirable outcomes (Oki and Kanae, 2006). The studies compiled in Table 3-2 illustrate the benefits of reducing GHG emissions for the Earth's freshwater systems. Emissions scenarios are rather similar until the 2050s. Their impacts, and thus the benefits of mitigation, tend to become more clearly marked by the end of the 21st century. For example, the fraction of the world population exposed to a 20th century 100-year flood is projected to be, at the end of the 21st century, three times higher per year for RCP8.5 than for RCP2.6 (Hirabayashi et al., 2013). Each degree of global warming (up to 2.7°C above preindustrial levels; Schewe et al., 2013) is projected to decrease renewable water resources by at least 20% for an additional 7% of the world population. The number of people with significantly decreased access to renewable groundwater resources is projected to be roughly 50% higher under RCP8.5 than under RCP2.6 (Portmann et al., 2013). The percentage of global population living in river basins with new or aggravated water scarcity is projected to increase with global warming, from 8% at 2°C to 13% at 5°C (Gerten et al., 2013).

3.5.1. Availability of Water Resources

About 80% of the world's population already suffers serious threats to its water security, as measured by indicators including water availability,

Table 3-2 | Effects of different greenhouse gas (GHG) emissions scenarios on hydrological changes and freshwater-related impacts of climate change on humans and ecosystems. Among the Special Report on Emission Scenarios (SRES) scenarios, GHG emissions are highest in A1f and A2, lower in A1 and B2, and lowest in B1. Representative Concentration Pathway 8.5 (RCP8.5) is similar to A2, while the lower emissions scenarios RCP6.0 and RCP4.5 are similar to B1. RCP2.6 is a very low emissions scenario (Figure 1-4 and Section 1.1.3.1 in Chapter 1). The studies in the table give global warming (GW: global mean temperature rise, quantified as the Coupled Model Intercomparison Project Phase 5 (CMIP5) model mean) over different reference periods, typically since pre-industrial. GW since pre-industrial is projected to be, for RCP8.5, approximately 2°C in the 2040s and 4°C in the 2090s. For RCP6.0, GW is 2°C in the 2060s and 2.5°C in the 2090s, while in RCP2.6, GW stays below 1.5°C throughout the 21st century (Figure 1-4 in Chapter 1). Population scenario SSP2 assumes a medium population increase. The number of GCMs that were used in the studies is provided.

Type of hydrological change or impact	Description of indicator	Hydrological change or impact in different emissions scenarios or for different degrees of global warming (GW)	Reference
Decrease of renewable water resources, global scale	Percent of global population affected by a water resource decrease of more than 20% as compared to the 1990s (mean of 5 General Circulation Models (GCMs) and 11 global hydrological models, population scenario SSP2)	Up to 2°C above the 1990s (GW 2.7°C), each degree of GW affects an additional 7%	Schewe et al. (2013)
Decrease of renewable groundwater resources, global scale	Percent of global population affected by a groundwater resource decrease of more than 10% by the 2080s as compared to the 1980s (mean and range of 5 GCMs, population scenario SSP2)	• RCP2.6: 24% (11–39%) • RCP4.5: 26% (23–32%) • RCP6.0: 32% (18–45%) • RCP8.5: 38% (27–50%)	Portmann et al. (2013)
Exposure to floods, global scale	Percent of global population annually exposed, in the 2080s, to a flood corresponding to the 100-year flood discharge for the 1980s (mean and range of 5–11 GCMs, population constant at 2005 values)	• RCP2.6: 0.4% (0.2–0.5%) • RCP4.5: 0.6% (0.4–1.0%) • RCP6.0: 0.7% (0.3–1.1%) • RCP8.5: 1.2% (0.6–1.7%) • GW 2°C: 0.5% (0.3–0.6%) • GW 4°C: 1.2% (0.8–2.2%) • 1980s: 0.1% (0.04–0.16%)	Hirabayashi et al. (2013)
Change in irrigation water demand, global scale	Change of required irrigation water withdrawals by the 2080s (on area irrigated around 2000) as compared to the 1980s (range of 3 GCMs)	• RCP2.6: –0.2 to 1.6% • RCP4.5: 1.9–2.8% • RCP8.5: 6.7–10.0%	Hanasaki et al. (2013)
River flow regime shifts from perennial to intermittent and vice versa, global scale	Percent of global land area (except Greenland and Antarctica) affected by regime shifts between the 1970s and the 2050s (range of 2 GCMs)	• SRES B2: 5.4–6.7% • SRES A2: 6.3–7.0%	Döll and Müller Schmied (2012)
Water scarcity	Percent of global population living in countries with less than 1300 $m^3\ yr^{-1}$ of per capita blue water resources in the 2080s (mean of 17 GCMs, population constant at 2000 values)	No significant differences between SRES B1 and A2	Gerten et al. (2011)
New or aggravated water scarcity	Percent of global population living in river basins with new or aggravated water scarcity around 2100 as compared to 2000 (less than 1000 $m^3\ yr^{-1}$ of per capita blue water resources) (median of 19 GCMs, population constant at 2000 values)	• GW 2°C: 8% • GW 3.5°C: 11% • GW 5°C: 13%	Gerten et al. (2013)
Exposure to water scarcity	Population in water-stressed watersheds (less than 1000 $m^3\ yr^{-1}$ of per capita blue water resources) exposed to an increase in stress (1 GCM)	For emissions scenarios with 2°C target, compared to SRES A1: • 5–8% impact reduction in 2050 • 10–20% reduction in 2100	Arnell et al. (2013)
Change of groundwater recharge in the whole of Australia	Probability that groundwater recharge decreases to less than 50% of the 1990s value by 2050 (16 GCMs)	• GW 1.4°C: close to 0 almost everywhere • GW 2.8°C: in western Australia 0.2–0.6, in central Australia 0.2–0.3, elsewhere close to 1	Crosbie et al. (2013a)
Change in groundwater recharge in East Anglia, UK	Percent change between baseline and future groundwater recharge, in %, by the 2050s (1 GCM)	• SRES B1: –22% • SRES A1f: –26%	Holman et al. (2009)
Change of river discharge, groundwater recharge, and hydraulic head in groundwater in two regions of Denmark	Changes between the 1970s and the 2080s (1 regional climate model)	Differences between SRES B2 and A2 are very small compared to the changes between the 1970s and the 2080s in each scenario.	van Roosmalen et al. (2007)
River flow regime shift for river in Uganda	Shift from bimodal to unimodal (1 GCM)	Occurs in scenarios with GW of at least 4.3°C but not for smaller GW.	Kingston and Taylor (2010)
Agricultural (soil moisture) droughts in France	Mean duration, affected area, and magnitude of short and long drought events throughout the 21st century (1 GCM)	Smaller increases over time for SRES B1 than for A2 and A1B.	Vidal et al. (2012)
Salinization of artificial coastal freshwater lake IJsselmeer in the Netherlands (a drinking water source) due to seawater intrusion	(1) Daily probability of exceedance of maximum allowable concentration (MAC) of chloride (150 mg L^{-1}) (2) Maximum duration of MAC exceedance (2050, 1 GCM)	• Reference period 1997–2007 (GW 0.8°C): (1) 2.5%, (2) 103 days • GW 1.8°C, no change in atmospheric circulation: (1) 3.1%, (2) 124 days • GW 2.8°C and change in atmospheric circulation: (1) 14.3%, (2) 178 days	Bonte and Zwolsman (2010)
Decrease of hydropower production at Lake Nasser, Egypt	Reduction of mean annual hydropower production by the 2080s compared to hydropower production 1950–99 (11 GCMs)	• SRES B1: 8% • SRES A2: 7%	Beyene et al. (2010)
Reduction of usable capacity of thermal power plants in Europe and USA due to low river flow and excessive water temperature	Number of days per year with a capacity reduction of more than 50% (for existing power plants) (2031–2060, 3 GCMs)	• Without climate change: 16 • SRES B1: 22 • SRES A2: 24	van Vliet et al. (2012)
Flood damages in Europe (EU27)	(1) Expected annual damages, in 2006 (2) Expected annual population exposed (2080s, 2 GCMs)	• SRES B2: (1) 14–15 billion € yr^{-1}, (2) 440,000–470,000 people • SRES A2: (1) 18–21 billion € yr^{-1}, (2) 510,000–590,000 people • Reference period: (1) 6.4 billion € yr^{-1}, (2) 200,000 people	Feyen et al. (2012)

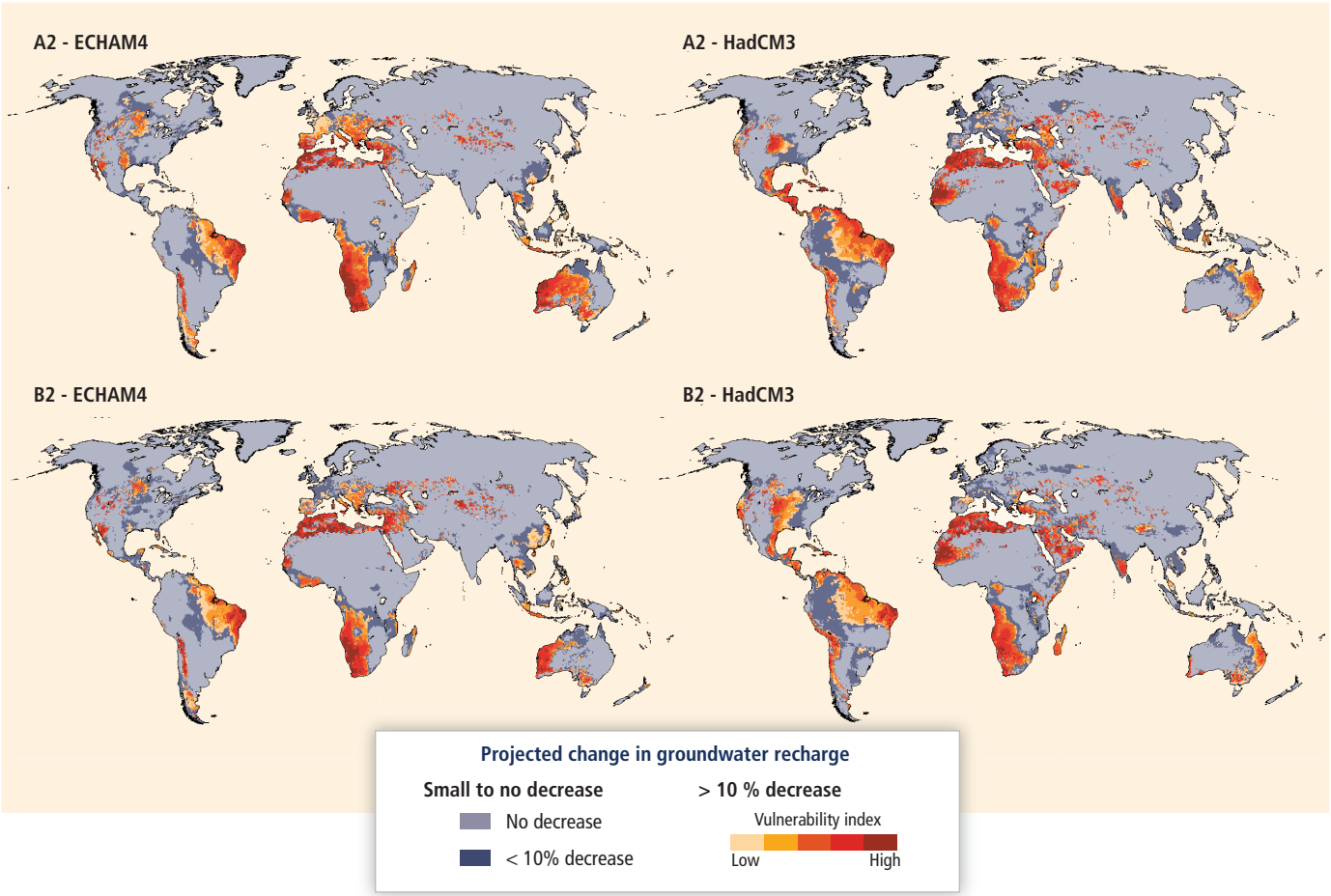


Figure 3-7 | Human vulnerability to climate change–induced decreases of renewable groundwater resources by the 2050s. Lower (Special Report on Emission Scenarios (SRES) B2) and higher (SRES A2) emissions pathways are interpreted by two global climate models. The higher the vulnerability index (computed by multiplying percentage decrease of groundwater recharge by a sensitivity index), the higher is the vulnerability. The index is defined only for areas where groundwater recharge is projected to decrease by at least 10% relative to 1961–1990 (Döll, 2009).

water demand, and pollution (Vörösmarty et al., 2010). Climate change can alter the availability of water and therefore threaten water security as defined by UNESCO (2011).

Global-scale analyses so far have concentrated on measures of resource availability rather than the multi-dimensional indices used in Vörösmarty et al. (2010). All have simulated future river flows or groundwater recharge using global-scale hydrological models. Some have assessed future availability based on runoff per capita (Hayashi et al., 2010; Arnell et al., 2011, 2013; Fung et al., 2011; Murray et al., 2012; Gerten et al., 2013; Gosling and Arnell, 2013; Schewe et al., 2013), whilst others have projected future human withdrawals and characterized availability by the ratio of withdrawals to availability from runoff or recharge (Arnell et al., 2011; Gosling and Arnell, 2013; Hanasaki et al., 2013). A groundwater vulnerability index was constructed that combined future reductions of renewable groundwater resources with water scarcity, dependence on groundwater, and the Human Development Index (Figure 3-7) (Döll, 2009). There are several key conclusions from this set of studies. First, the spatial distribution of the impacts of climate change on resource availability varies considerably between climate models, and strongly with the pattern of projected rainfall change. There is strong consistency in projections of reduced availability around the Mediterranean and parts of southern Africa, but much greater variation in projections for south and East Asia. Second, some water-stressed areas see increased runoff in the future (Section 3.4.4), and therefore less exposure to water resources stress. Third, over the next few decades and for increases in global mean temperature of less than around 2°C above preindustrial, changes in population will generally have a greater effect on changes in resource availability than will climate change. Climate change would, however, regionally exacerbate or offset the effects of population pressures. Fourth, estimates of future water availability are sensitive not only to climate and population projections and population assumptions, but also to the choice of hydrological impact model (Schewe et al., 2013) and to the adopted measure of stress or scarcity. As an indication of the potential magnitude of the impact of climate change, Schewe et al. (2013) estimated that about 8% of the global population would see a severe reduction in water resources (a reduction in runoff either greater than 20% or more than the standard deviation of current annual runoff) with a 1°C rise in global mean temperature (compared to the 1990s), rising to 14% at 2°C and 17% at 3°C; the spread across climate and hydrological models was, however, large.

Under climate change, reliable surface water supply is expected to decrease due to increased variability of river flow that is due in turn to

Frequently Asked Questions

FAQ 3.2 | How will the availability of water resources be affected by climate change?

Climate models project decreases of renewable water resources in some regions and increases in others, albeit with large uncertainty in many places. Broadly, water resources are projected to decrease in many mid-latitude and dry subtropical regions, and to increase at high latitudes and in many humid mid-latitude regions (*high agreement*, *robust evidence*). Even where increases are projected, there can be short-term shortages due to more variable streamflow (because of greater variability of precipitation) and seasonal reductions of water supply due to reduced snow and ice storage. Availability of clean water can also be reduced by negative impacts of climate change on water quality; for instance, the quality of lakes used for water supply could be impaired by the presence of algae-producing toxins.

increased precipitation variability and decreased snow and ice storage. Under these circumstances, it might be beneficial to take advantage of the storage capacity of groundwater and to increase groundwater withdrawals (Kundzewicz and Döll, 2009). However, this option is sustainable only where, over the long term, withdrawals remain well below recharge, while care must also be taken to avoid excessive reduction of groundwater outflow to rivers. Therefore, groundwater cannot be expected to ease freshwater stress where climate change is projected to decrease groundwater recharge and thus renewable groundwater resources (Kundzewicz and Döll, 2009). The percentage of projected global population (SSP2 population scenario) that will suffer from a decrease of renewable groundwater resources of more than 10% between the 1980s and the 2080s was computed to range from 24% (mean based on five GCMs, range 11 to 39%) for RCP2.6 to 38% (range 27 to 50%) for RCP8.5 (Portmann et al., 2013; see also Table 3-2). The land area affected by decreases of groundwater resources increases linearly with global mean temperature rise between 0°C and 3°C. For each degree of global mean temperature rise, an additional 4% of the global land area is projected to suffer a groundwater resources decrease of more than 30%, and an additional 1% to suffer a decrease of more than 70% (Portmann et al., 2013).

3.5.2. Water Uses

3.5.2.1. Agriculture

Water demand and use for food and livestock feed production is governed not only by crop management and its efficiency, but also by the balance between atmospheric moisture deficit and soil water supply. Thus, changes in climate (precipitation, temperature, radiation) will affect the water demand of crops grown in both irrigated and rainfed systems. Using projections from 19 CMIP3 GCMs forced by SRES A2 emissions to drive a global vegetation and hydrology model, climate change by the 2080s would hardly alter the global irrigation water demand of major crops in areas currently equipped for irrigation (Konzmann et al., 2013). However, there is *high confidence* that irrigation demand will increase significantly in many areas (by more than 40% across Europe, USA, and parts of Asia). Other regions—including major irrigated areas in India, Pakistan, and southeastern China—might experience a slight decrease in irrigation demand, due for example to higher precipitation, but only under some climate change scenarios (also see Biemans et al., 2013). Using seven global hydrological models but a limited set of CMIP5 projections, Wada et al. (2013) suggested a global increase in irrigation demand by the 2080s (ensemble average 7 to 21% depending on emissions scenario), with a pronounced regional pattern, a large inter-model spread, and possible seasonal shifts in crop water demand and consumption. By contrast, based on projections from two GCMs and two emissions scenarios, a slight global decrease in crop water deficits was suggested in both irrigated and rainfed areas by the 2080s, which can be explained partly by a smaller difference between daily maximum and minimum temperatures (Zhang and Cai, 2013). As in other studies, region-to-region variations were very heterogeneous.

Where poor soil is not a limiting factor, physiological and structural crop responses to elevated atmospheric CO_2 concentration (CO_2 fertilization) might partly cancel out the adverse effects of climate change, potentially reducing global irrigation water demand (Konzmann et al., 2013; see also Box CC-VW). However, even in this optimistic case, increases in irrigation water demand by >20% are still projected under most scenarios for some regions, such as southern Europe. In general, future irrigation demand is projected to exceed local water availability in many places (Wada et al., 2013). The water demand to produce a given amount of food on either irrigated or rainfed cropland will increase in many regions due to climate change alone (Gerten et al., 2011, projections from 17 CMIP3 GCMs, SRES A2 emissions), but this increase might be moderated by concurrent increases in crop water productivity due to CO_2 effects, that is, decreases in per-calorie water demand. The CO_2 effects may thus lessen the global number of people suffering water scarcity; nonetheless, the effect of anticipated population growth is *likely* to exceed those of climate and CO_2 change on agricultural water demand, use, and scarcity (Gerten et al., 2011).

Rainfed agriculture is vulnerable to increasing precipitation variability. Differences in yield and yield variability between rainfed and irrigated land may increase with changes in climate and its variability (e.g., Finger et al., 2011). Less irrigation water might be required for paddy rice cultivation in monsoon regions where rainfall is projected to increase and the crop growth period to become shorter (Yoo et al., 2013). Water demand for rainfed crops could be reduced by better management (Brauman et al., 2013), but unmitigated climate change may counteract such efforts, as shown in a global modeling study (Rost et al., 2009). In

some regions, expansion of irrigated areas or increases of irrigation efficiencies may overcome climate change impacts on agricultural water demand and use (McDonald and Girvetz, 2013).

3.5.2.2. Energy Production

Hydroelectric and thermal power plants, and the irrigation of bioenergy crops (Box CC-WE), require large amounts of water. This section assesses the impact of hydrological changes (as described in Section 3.4) on hydroelectric and thermal power production. The impacts of changes in energy production due to climate change mitigation efforts are discussed in Section 3.7.2.1, while the economic implications of the impact of climate change on thermal power and hydropower production as well as adaptation options are assessed in Chapter 10.

Climate change affects hydropower generation through changes in the mean annual streamflow, shifts of seasonal flows, and increases of streamflow variability (including floods and droughts), as well as by increased evaporation from reservoirs and changes in sediment fluxes. Therefore, the impact of climate change on a specific hydropower plant will depend on the local change of these hydrological characteristics, as well as on the type of hydropower plant and on the (seasonal) energy demand, which will itself be affected by climate change (Golombek et al., 2012). Run-of-river power plants are more susceptible to increased flow variability than plants at dams. Projections of future hydropower generation are subject to the uncertainty of projected precipitation and streamflow. For example, projections to the 2080s of hydropower generation in the Pacific Northwest of the USA range from a decrease of 25% to an increase of 10% depending on the climate model (Markoff and Cullen, 2008). Based on an ensemble of 11 GCMs, hydropower generation at the Aswan High Dam (Egypt) was computed to remain constant until the 2050s but to decrease, following the downward trend of mean annual river discharge, to 90% (ensemble mean) of current mean annual production under both SRES B1 and A2 (Beyene et al., 2010; see also Table 3-2). In snow-dominated basins, increased discharge in winter, smaller and earlier spring floods, and reduced discharge in summer have already been observed (Section 3.2.6) and there is *high confidence* that these trends will continue. In regions with high electricity demands for heating, this makes the annual hydrograph more similar to seasonal variations in electricity demand, reducing required reservoir capacities and providing opportunities for operating dams and power stations to the benefit of riverine ecosystems (Renofalt et al., 2010; Golombek et al., 2012). In regions with high electricity demand for summertime cooling, however, this seasonal streamflow shift is detrimental. In general, climate change requires adaptation of operating rules (Minville et al., 2009; Raje and Mujumdar, 2010) which may, however, be constrained by reservoir capacity. In California, for example, high-elevation hydropower systems with little storage, which rely on storage in the snowpack, are projected to yield less hydropower owing to the increased occurrence of spills, unless precipitation increases significantly (Madani and Lund, 2010). Storage capacity expansion would help increase hydropower generation but might not be cost effective (Madani and Lund, 2010).

Regarding water availability for cooling of thermal power plants, the number of days with a reduced useable capacity is projected to increase in Europe and the USA, owing to increases in stream temperatures and the incidence of low flows (Flörke et al., 2012; van Vliet et al., 2012; see also Table 3-2). Warmer cooling water was computed to lower thermal power plant efficiency and thus electricity production by 1.5 to 3% in European countries by the 2080s under emissions scenario SRES A1B (Golombek et al., 2012).

3.5.2.3. Municipal Services

Under climate change, water utilities are confronted by the following (Bates et al., 2008; Jiménez, 2008; van Vliet and Zwolsman, 2008; Black and King, 2009; Brooks et al., 2009; Whitehead et al., 2009a; Bonte and Zwolsman, 2010; Hall and Murphy, 2010; Mukhopadhyay and Dutta, 2010; Qin et al., 2010; Chakraborti et al., 2011; Major et al., 2011; Thorne and Fenner, 2011; Christierson et al., 2012):

- Higher ambient temperatures, which reduce snow and ice volumes and increase the evaporation rate from lakes, reservoirs, and aquifers. These changes decrease natural storage of water, and hence, unless precipitation increases, its availability. Moreover, higher ambient temperatures increase water demand, and with it the competition for the resource (*medium* to *high agreement*, *limited evidence*).
- Shifts in timing of river flows and possible more frequent or intense droughts, which increase the need for artificial water storage.
- Higher water temperatures, which encourage algal blooms and increase risks from cyanotoxins and natural organic matter in water sources, requiring additional or new treatment of drinking water (*high agreement*, *medium evidence*). On the positive side, biological water and wastewater treatment is more efficient when the water is warmer (Tchobanoglous et al., 2003).
- Possibly drier conditions, which increase pollutant concentrations. This is a concern especially for groundwater sources that are already of low quality, even when pollution is natural as in India and Bangladesh, North and Latin America and Africa; here arsenic, iron, manganese, and fluorides are often a problem (Black and King, 2009).
- Increased storm runoff, which increases loads of pathogens, nutrients, and suspended sediment.
- Sea level rise, which increases the salinity of coastal aquifers, in particular where groundwater recharge is also expected to decrease.

Climate change also impacts water quality indirectly. For instance, at present many cities rely on water from forested catchments that requires very little treatment. More frequent and severe forest wildfires could seriously degrade water quality (Emelko et al., 2011; Smith et al., 2011).

Many drinking water treatment plants—especially small ones—are not designed to handle the more extreme influent variations that are to be expected under climate change. These demand additional or even different infrastructure capable of operating for up to several months per year, which renders wastewater treatment very costly, notably in rural areas (Zwolsman et al., 2010; Arnell et al., 2011).

Sanitation technologies vary in their resilience to climate impacts (Howard et al., 2010). For sewage, three climatic conditions are of interest (NACWA, 2009; Zwolsman et al., 2010):

- Wet weather: heavier rainstorms mean increased amounts of water and wastewater in combined systems for short periods. Current

designs, based on critical "design storms" defined through analysis of historical precipitation data, therefore need to be modified. New strategies to adapt to and mitigate urban floods need to be developed, considering not only climate change but also urban design, land use, the "heat island effect," and topography (Changnon, 1969).

- Dry weather: soil shrinks as it dries, causing water mains and sewers to crack and making them vulnerable to infiltration and exfiltration of water and wastewater. The combined effects of higher temperatures, increased pollutant concentrations, longer retention times, and sedimentation of solids may lead to increasing corrosion of sewers, shorter asset lifetimes, more drinking water pollution, and higher maintenance costs.
- Sea level rise: intrusion of brackish or salty water into sewers necessitates processes that can handle saltier wastewater.

Increased storm runoff implies the need to treat additional wastewater when combined sewers are used, as storm runoff adds to sewage; in addition, the resulting mixture has a higher content of pathogens and pollutants. Under drier conditions higher concentrations of pollutants in wastewater, of any type, are to be expected and must be dealt with (Whitehead et al., 2009a,b; Zwolsman et al., 2010). The cost may rule this out in low-income regions (Chakraborti et al., 2011; Jiménez, 2011). The disposal of wastewater or fecal sludge is a concern that is just beginning to be addressed in the literature (Seidu et al., 2013).

3.5.2.4. Freshwater Ecosystems

Freshwater ecosystems are composed of biota (animals, plants, and other organisms) and their abiotic environment in slow-flowing surface waters such as lakes, man-made reservoirs, or wetlands; in fast-flowing surface waters such as rivers and creeks; and in the groundwater. They have suffered more strongly from human activities than have marine and terrestrial ecosystems. Between 1970 and 2000, populations of freshwater species included in the Living Planet Index declined on average by 50%, compared to 30% for marine and also for terrestrial species (Millennium Ecosystem Assessment, 2005). Climate change is an additional stressor of freshwater ecosystems, which it affects not only through increased water temperatures (discussed in Section 4.3.3.3) but also by altered streamflow regimes, river water levels, and extent and timing of inundation (Box CC-RF). Wetlands in dry environments are hotspots of biological diversity and productivity, and their biotas are at risk of extinction if runoff decreases and the wetland dries out (as described for Mediterranean-type temporary ponds by Zacharias and Zamparas, 2010). Freshwater ecosystems are also affected by water quality changes induced by climate change (Section 3.2.5), and by human adaptations to climate change-induced increases of streamflow variability and flood risk, such as the construction of dykes and dams (Ficke et al., 2007; see also Section 3.7.2).

3.5.2.5. Other Uses

In addition to direct impacts, vulnerabilities, and risks in water-related sectors, indirect impacts of hydrological changes are expected for navigation, transportation, tourism, and urban planning (Pinter et al., 2006; Koetse and Rietveld, 2009; Rabassa, 2009; Badjeck et al., 2010; Beniston, 2012). Social and political problems can result from hydrological changes. For example, water scarcity and water overexploitation may increase the risks of violent conflicts and nation-state instability (Barnett and Adger, 2007; Burke et al. 2009; Buhaug et al., 2010; Hsiang et al., 2011). Snowline rise and glacier shrinkage are *very likely* to impact environmental, hydrological, geomorphological, heritage, and tourism resources in cold regions (Rabassa, 2009), as already observed for tourism in the European Alps (Beniston, 2012). Although most impacts will be adverse, some might be beneficial.

3.6. Adaptation and Managing Risks

In the face of hydrological changes and freshwater-related impacts, vulnerability, and risks due to climate change, there is need for adaptation and for increasing resilience. Managing the changing risks due to the impacts of climate change is the key to adaptation in the water sector (IPCC, 2012), and risk management should be part of decision making and the treatment of uncertainty (ISO, 2009). Even to exploit the positive impacts of climate change on freshwater systems, adaptation is generally required.

Frequently Asked Questions

FAQ 3.3 | How should water management be modified in the face of climate change?

Managers of water utilities and water resources have considerable experience in adapting their policies and practices to the weather. But in the face of climate change, long-term planning (over several decades) is needed for a future that is highly uncertain. A flexible portfolio of solutions that produces benefits regardless of the impacts of climate change ("low-regret" solutions) and that can be implemented adaptively, step by step, is valuable because it allows policies to evolve progressively, thus building on—rather than losing the value of—previous investments. Adaptive measures that may prove particularly effective include rainwater harvesting, conservation tillage, maintaining vegetation cover, planting trees in steeply sloping fields, mini-terracing for soil and moisture conservation, improved pasture management, water reuse, desalination, and more efficient soil and irrigation water management. Restoring and protecting freshwater habitats, and managing natural floodplains, are additional adaptive measures that are not usually part of conventional management practice.

3.6.1. Options

There is growing agreement that an adaptive approach to water management can successfully address uncertainty due to climate change. Although there is *limited evidence* of the effectiveness of such an approach, the evidence is growing (Section 3.6.2). Many practices identified as adaptive were originally reactions to climate variability. Climate change provides many opportunities for "low-regret" solutions, capable of yielding social and/or economic benefits and adaptive both to variability and to change (Table 3-3). Adaptive techniques include scenario planning, experimental approaches that involve learning from experience, and the development of flexible solutions that are resilient to uncertainty. A program of adaptation typically mixes "hard" infrastructural and "soft" institutional measures (Bates et al., 2008; Cooley, 2008; Mertz et al., 2009; Sadoff and Muller, 2009; UNECE, 2009; Olhoff and Schaer, 2010).

To avoid adaptation that goes wrong—"maladaptation"—scientific research results should be analyzed during planning. Low-regret solutions, such as those for which moderate investment clearly increases the capacity to cope with projected risks or for which the investment is justifiable under all or almost all plausible scenarios, should be considered explicitly. Involving all stakeholders, reshaping planning processes, coordinating the management of land and water resources, recognizing linkages between water quantity and quality, using surface water and groundwater conjunctively, and protecting and restoring natural systems are examples of principles that can beneficially inform planning for adaptation (World Bank, 2007).

Integrated Water Resource Management continues to be a promising instrument for exploring adaptation to climate change. It can be joined with a Strategic Environmental Assessment to address broader considerations. Attention is currently increasing to "robust measures" (European Communities, 2009), which are measures that perform well under different future conditions and clearly optimize prevailing strategies (Sigel et al., 2010). Barriers to adaptation are discussed in detail in Section 16.4. Barriers to adaptation in the freshwater sector include lack of human and institutional capacity, lack of financial resources, lack of awareness, and lack of communication (Browning-Aiken et al., 2007; Burton, 2008; Butscher and Huggenberger, 2009; Zwolsman et al., 2010). Institutional structures can be major barriers to adaptation (Goulden et al., 2009; Engle and Lemos, 2010; Huntjens et al., 2010; Stuart-Hill and Schulze, 2010; Ziervogel et al., 2010; Wilby and Vaughan, 2011; Bergsma et al., 2012); structures that promote participation of and collaboration between stakeholders tend to encourage adaptation. Some adaptation measures may not pass the test of workability in an uncertain future (Campbell et al., 2008), and uncertainty (Section 3.6.2) can be another significant barrier.

Case studies of the potential effectiveness of adaptation measures are increasing. Changes in operating practices and infrastructure improvements could help California's water managers respond to changes in the volume and timing of supply (Medellin-Azuara et al., 2008; Connell-Buck et al., 2011). Other studies include evaluations of the effectiveness of different adaptation options in Washington state, USA (Miles et al., 2010) and the Murray-Darling basin, Australia (Pittock and Finlayson, 2011), and of two dike-heightening strategies in the Netherlands (Hoekstra and de Kok, 2008). Such studies have demonstrated that it is technically feasible in general to adapt to projected climate changes, but not all have considered how adaptation would be implemented.

3.6.2. Dealing with Uncertainty in Future Climate Change

One of the key challenges in factoring climate change into water resources management lies in the uncertainty. Some approaches (e.g., in England and Wales; Arnell, 2011) use a small set of climate scenarios to characterize the potential range of impacts on water resources and flooding. Others (e.g., Brekke et al., 2008; Lopez et al., 2009; Christierson et al., 2012; Hall et al., 2012) use very large numbers of scenarios to generate likelihood distributions of indicators of impact for use in risk assessment. However, it has been argued (Hall, 2007; Stainforth et al., 2007; Dessai et al., 2009) that attempts to construct probability distributions of impacts are misguided because of "deep" uncertainty, which arises because analysts do not know, or cannot agree on, how the climate system and water management systems may change, how models represent possible changes, or how to value the desirability of different outcomes. Stainforth et al. (2007) therefore argue that it is impossible in practice to construct robust quantitative probability distributions of climate change impacts, and that climate change uncertainty needs to be represented differently, for example by using fewer plausible scenarios and interpreting the outcomes of scenarios less quantitatively.

Some go further, arguing that climate models are not sufficiently robust or reliable to provide the basis for adaptation (Koutsoyiannis et al., 2008; Anagnostopoulos et al., 2010; Blöschl and Montanari, 2010; Wilby, 2010), because they are frequently biased and do not reproduce the temporal characteristics (specifically the persistence or "memory") often found in hydrological records. It has been argued (Lins and Cohn, 2011; Stakhiv, 2011) that existing water resources planning methods are sufficiently robust to address the effects of climate change. This view of climate model performance has been challenged and is the subject of some debate (Koutsoyiannis et al., 2009, 2011; Huard, 2011); the critique also assumes that adaptation assessment procedures would use only climate scenarios derived directly from climate model simulations.

Addressing uncertainty in practice by quantifying it through some form of risk assessment, however, is only one way of dealing with uncertainty. A large and increasing literature recommends that water managers should move from the traditional "predict and provide" approach toward adaptive water management (Pahl-Wostl, 2007; Pahl-Wostl et al., 2008; Matthews and Wickel, 2009; Mysiak et al., 2009; Huntjens et al., 2012; Short et al., 2012; Gersonius et al., 2013) and the adoption of resilient or "no-regrets" approaches (WWAP, 2009; Henriques and Spraggs, 2011). Approaches that are resilient to uncertainty are not entirely technical (or supply-side), and participation and collaboration amongst all stakeholders are central to adaptive water management. However, although climate change is frequently cited as a key motive, there is very little published guidance on how to implement the adaptive water management approach. Some examples are given in Ludwig et al. (2009). The most comprehensive overview of adaptive water

Table 3-3 | Categories of climate change adaptation options for the management of freshwater resources.

Category	Option	May assist both adaptation and mitigation
Institutional	Support integrated water resources management, including the integrated management of land considering specifically negative and positive impacts of climate change	X
	Promote synergy of water and energy savings and efficient use	X
	Identify "low-regret policies" and build a portfolio of relevant solutions for adaptation	X
	Increase resilience by forming water utility network working teams	
	Build adaptive capacity	
	Improve and share information	X
	Adapt the legal framework to make it instrumental for addressing climate change impacts	X
	Develop financial tools (credit, subsidies, and public investment) for the sustainable management of water, and for considering poverty eradication and equity	
Design and operation	Design and apply decision-making tools that consider uncertainty and fulfill multiple objectives	
	Revise design criteria of water infrastructure to optimize flexibility, redundancy, and robustness	
	Ensure plans and services are robust, adaptable, or modular; give good value; are maintainable; and have long-term benefits, especially in low-income countries	X
	Operate water infrastructure so as to increase resilience to climate change for all users and sectors	
	When and where water resources increase, alter dam operations to allow freshwater ecosystems to benefit	
	Take advantage of hard and soft adaptation measures	X
	Carry out programs to protect water resources in quantity and quality	
	Increase resilience to climate change by diversifying water sources[a] and improving reservoir management	X
	Reduce demand by controlling leaks, implementing water-saving programs, cascading and reusing water	X
	Improve design and operation of sewers, sanitation, and wastewater treatment infrastructure to cope with variations in influent quantity and quality	
	Provide universal sanitation with technology locally adapted, and provide for proper disposal and reintegration of used water into the environment or for its reuse	
Reduce impact of natural disasters	Implement monitoring and early warning systems	
	Develop contingency plans	
	Improve defenses and site selection for key infrastructure that is at risk of floods	
	Design cities and rural settlements to be resilient to floods	
	Seek and secure water from a diversity (spatially and source-type) of sources to reduce impacts of droughts and variability in water availability	
	Promote both the reduction of water demand and the efficient use of water by all users	
	Promote switching to more appropriate crops (drought-resistant, salt-resistant; low water demand)	X
	Plant flood- or drought-resistant crop varieties	
Agricultural irrigation	Improve irrigation efficiency and reduce demand for irrigation water	X
	Reuse wastewater to irrigate crops and use soil for carbon sequestration	X
Industrial use	When selecting alternative sources of energy, assess the need for water	X
	Relocate water-thirsty industries and crops to water-rich areas	
	Implement industrial water efficiency certifications	X

[a]This includes water reuse, rain water harvesting, and desalination, among others.

Sources: Vörösmarty et al. (2000); Marsalek et al. (2006); Mogaka et al. (2006); Dillon and Jiménez (2008); Jiménez and Asano (2008); Keller (2008); McCafferty (2008); McGuckin (2008); Seah (2008); UN-HABITAT (2008); Thöle (2008); Andrews (2009); Bahri (2009); Munasinghe (2009); NACWA (2009); OFWAT (2009); Reiter (2009); Whitehead et al. (2009b); de Graaf and der Brugge (2010); Dembo (2010); Godfrey et al. (2010); Howard et al. (2010); Mackay and Last (2010); Mukhopadhyay and Dutta (2010); OECD (2010); Renofalt et al. (2010); Zwolsman et al. (2010); Arkell (2011a, 2011b); Elliott et al. (2011); Emelko et al. (2011); Jiménez (2011); Kingsford (2011); Major et al. (2011); Sprenger et al. (2011); UNESCO (2011); Wang X. et al. (2011); Bowes et al. (2012).

management that explicitly incorporates climate change and its uncertainty is the three-step framework of the U.S. Water Utilities Climate Alliance (WUCA, 2010): system vulnerability assessment, utility planning using decision-support methods, and decision making and implementation. Planning methods for decision support include classic decision analysis, traditional scenario planning, and robust decision making (Lempert et al., 1996, 2006; Nassopoulos et al., 2012). The latter was applied by the Inland Empire Utilities Agency, supplying water to a region in Southern California (Lempert and Groves, 2010). This led to the refinement of the company's water resource management plan, making it more robust to three particularly challenging aspects of climate change that were identified by the scenario analysis. Another framework, based on risk assessment, is the threshold-scenario framework of Freas et al. (2008).

3.6.3. Costs of Adaptation to Climate Change

Calculating the global cost of adaptation in the water sector is a difficult task and results are highly uncertain. Globally, to maintain water services at non-climate change levels to the year 2030 in more than 200 countries, total adaptation costs for additional infrastructure were estimated as US$531 billion for the SRES A1B scenario (Kirshen, 2007). Including two further costs, for reservoir construction because the best locations have already been taken, and for unmet irrigation demands, total water sector adaptation costs were estimated as US$225 billion, or US$11 billion per year for the SRES A1B scenario (UNFCCC, 2007).

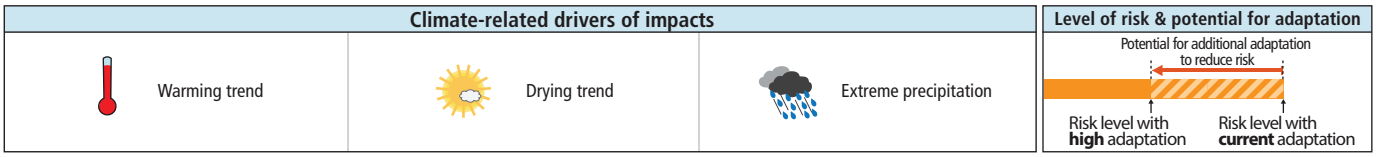
Average annual water supply and flood protection costs to 2050 for restoring service to non-climate change levels were estimated to be US$19.7 billion for a dry GCM projection of the SRES A2 scenario and US$14.4 billion for a wet GCM projection (Ward et al., 2010; World Bank, 2010). Annual urban infrastructure costs, primarily for wastewater treatment and urban drainage, were US$13.0 billion (dry) and US$27.5 billion (wet). Under both GCM projections for the A2 scenario, the water sector accounted for about 50% of total global adaptation cost, which was distributed regionally in the proportions: East Asia/Pacific, 20%; Europe/Central Asia, 10%; Latin America/Caribbean, 20%; Middle East/North Africa, 5%; South Asia, 20%; sub-Saharan Africa, 20%.

Annual costs for adaptation to climate change in sub-Saharan Africa are estimated as US$1.1 to 2.7 billion for current urban water infrastructure, plus US$1.0 to 2.5 billion for new infrastructure to meet the 2015 Millennium Development Goals (Muller, 2007). These estimates assume a 30% reduction in stream flow and an increase of at least 40% in the unit cost of water. Annual estimates of adaptation costs for urban water storage are US$0.05 to 0.15 billion for existing facilities and US$0.015 to 0.05 billion for new developments. For wastewater treatment, the equivalent estimates are US$0.1 to 0.2 billion and US$0.075 to 0.2 billion.

3.6.4. Adaptation in Practice in the Water Sector

A number of water management agencies are beginning to factor climate change into processes and decisions (Kranz et al., 2010; Krysanova et al., 2010), with the amount of progress strongly influenced by institutional characteristics. Most of the work has involved developing methodologies to be used by water resources and flood managers (e.g., Rudberg et al., 2012), and therefore represents attempts to improve adaptive capacity. In England and Wales, for example, methodologies to gauge the effects of climate change on reliability of water supplies have evolved since the late 1990s (Arnell, 2011), and the strategic plans of water supply companies now generally allow for climate change. Brekke et al. (2009a) describe proposed changes to practices in the USA. Several studies report community-level activities to reduce exposure to current hydrological variability, regarded explicitly as a means of adapting to future climate change (e.g., Barrios et al., 2009; Gujja et al., 2009; Kashaigili et al., 2009; Yu et al., 2009).

Table 3-4 | Key risks from climate change and the potential for reducing risk through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments by chapter authors, with evaluation of evidence and agreement in supporting chapter sections. Each key risk is characterized as very low to very high. Risk levels are presented in three time frames: the present, near term (here assessed over 2030–2040), and longer term (here assessed over 2080–2100). Sources: Xie et al., 2006; Döll, 2009; Kaser et al., 2010; Arnell et al., 2011; Huss, 2011; Jóhannesson et al., 2012; Seneviratne et al., 2012; Arnell and Gosling, 2013; Dankers et al., 2013; Gosling and Arnell, 2013; Hanasaki et al., 2013; Hirabayashi et al., 2013; Kundzewicz et al., 2013; Portmann et al., 2013; Radić et al., 2013; Schewe et al., 2013; WGI AR5 Chapter 13.



Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Flood risks associated with climate change increase with increasing greenhouse gas emissions. (*robust evidence, high agreement*) [3.4.8]	By 2100, the number of people exposed annually to a 20th-century 100-year flood is projected to be three times greater for very high emissions (RCP8.5) than for very low emissions (RCP2.6).		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high
Climate change is projected to reduce renewable water resources significantly in most dry subtropical regions. (*robust evidence, high agreement*) [3.5.1]	This will exacerbate competition for water among agriculture, ecosystems, settlements, industry and energy production, affecting regional water, energy, and food security.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high
Because nearly all glaciers are too large for equilibrium with the present climate, there is a committed water-resources change during much of the 21st century, and changes beyond the committed change are expected due to continued warming; in glacier-fed rivers, total meltwater yields from stored glacier ice will increase in many regions during the next decades but decrease thereafter. (*robust evidence, high agreement*) [3.4.3]	Continued loss of glacier ice implies a shift of peak discharge from summer to spring, except in monsoonal catchments, and possibly a reduction of summer flows in the downstream parts of glacierized catchments.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high

Frequently Asked Questions

FAQ 3.4 | Does climate change imply only bad news about water resources?

There is good news as well as bad about water resources, but the good news is very often ambiguous. Water may become less scarce in regions that get more precipitation, but more precipitation will probably also increase flood risk; it may also raise the groundwater table, which could lead to damage to buildings and other infrastructure or to reduced agricultural productivity due to wet soils or soil salinization. More frequent storms reduce the risk of eutrophication and algal blooms in lakes and estuaries by flushing away nutrients, but increased storm runoff will carry more of those nutrients to the sea, exacerbating eutrophication in marine ecosystems, with possible adverse impacts as discussed in Chapter 30. Water and wastewater treatment yields better results under warmer conditions, as chemical and biological reactions needed for treatment perform in general better at higher temperatures. In many rivers fed by glaciers, there will be a "meltwater dividend" during some part of the 21st century, due to increasing rates of loss of glacier ice, but the continued shrinkage of the glaciers means that after several decades the total amount of meltwater that they yield will begin to decrease (*medium confidence*). An important point is that often impacts do not become "good news" unless investments are made to exploit them. For instance, where additional water is expected to become available, the infrastructure to capture that resource would need to be developed if it is not already in place.

3.7. Linkages with Other Sectors and Services

3.7.1. Impacts of Adaptation in Other Sectors on Freshwater Systems

Adaptation in other sectors such as agriculture, forestry, and industry might have impacts on the freshwater system, and therefore needs to be considered while planning adaptation in the water sector (Jiang et al., 2013). For example, better agricultural land management practices can also reduce erosion and sedimentation in river channels (Lu et al., 2010), while controlled flooding of agricultural land can alleviate the impacts of urban flooding. Increased irrigation upstream may limit water availability downstream (World Bank, 2007). A project designed for other purposes may also deliver increased resilience to climate change as a co-benefit, even without a specifically identified adaptive component (World Bank, 2007; Falloon and Betts, 2010).

3.7.2. Climate Change Mitigation and Freshwater Systems

3.7.2.1. Impact of Climate Change Mitigation on Freshwater Systems

Many measures for climate change mitigation affect freshwater systems. Afforestation generally increases evapotranspiration and decreases total runoff (van Dijk and Keenan, 2007). Afforestation of areas deemed suitable according to the Clean Development Mechanism–Afforestation/Reforestation provisions of the Kyoto Protocol (7.5 million km^2) would lead to large and spatially extensive decreases of long-term average runoff (Trabucco et al., 2008). On 80% of the area, runoff is computed to decline by more than 40%, while on 27% runoff decreases of 80 to 100% were computed, mostly in semiarid areas (Trabucco et al., 2008). For example, economic incentives for carbon sequestration may encourage the expansion of *Pinus radiata* timber plantations in the Fynbos biome of South Africa, with negative consequences for water supply and biodiversity; afforestation is viable to the forestry industry only because it pays less than 1% of the actual cost of streamflow reduction caused by replacing Fynbos by the plantations (Chisholm, 2010). In general, afforestation has beneficial impacts on soil erosion, local flood risk, water quality (nitrogen, phosphorus, suspended sediments), and stream habitat quality (van Dijk and Keenan, 2007; Trabucco et al., 2008; Wilcock et al., 2008).

Irrigated bioenergy crops and hydropower can have negative impacts on freshwater systems (Jacobson, 2009). In the USA, water use for irrigating biofuel crops could increase from 2% of total water consumption in 2005 to 9% in 2030 (King et al., 2010). Irrigating some bioenergy crops may cost more than the energy thus gained. In dry parts of India, pumping from a depth of 60 m for irrigating jatropha is estimated to consume more energy than that gained from the resulting higher crop yields (Gupta et al., 2010). For a biofuel scenario of the International Energy Agency, global consumptive irrigation water use for biofuel production is projected to increase from 0.5% of global renewable water resources in 2005 to 5.5% in 2030; biofuel production is projected to increase water consumption significantly in some countries (e.g., Germany, Italy, and South Africa), and to exacerbate the already serious water scarcity in others (e.g., Spain and China) (Gerbens-Leenes et al., 2012). Conversion of native Caatinga forest into rainfed fields for biofuels in semiarid northwestern Brazil may lead to a significant increase of groundwater recharge (Montenegro and Ragab, 2010), but there is a risk of soil salinization due to rising groundwater tables.

Hydropower generation leads to alteration of river flow regimes that negatively affect freshwater ecosystems, in particular biodiversity and abundance of riverine organisms (Döll and Zhang, 2010; Poff and Zimmerman, 2010), and to fragmentation of river channels by dams, with negative impacts on migratory species (Bourne et al., 2011). Hydropower operations often lead to discharge changes on hourly timescales that are detrimental to the downstream river ecosystem (Bruno et al., 2009; Zimmerman et al., 2010). However, release

management and structural measures like fish ladders can mitigate these negative impacts somewhat (Williams, 2008). In tropical regions, the global warming potential of hydropower, due to methane emissions from man-made reservoirs, may exceed that of thermal power; based on observed emissions of a tropical reservoir, this might be the case where the ratio of hydropower generated to the surface area of the reservoir is less than 1 MW km^{-2} (Gunkel, 2009).

CO_2 leakage to freshwater aquifers from saline aquifers used for carbon capture and storage (CCS) can lower pH by 1 to 2 units and increase concentrations of metals, uranium, and barium (Little and Jackson, 2010). Pressure exerted by gas injection can push brines or brackish water into freshwater parts of the aquifer (Nicot, 2008). Displacement of brine into potable water was not considered in a screening methodology for CCS sites in the Netherlands (Ramírez et al., 2010). Another emergent freshwater-related risk of climate mitigation is increased natural gas extraction from low-permeability rocks. The required hydraulic fracturing process ("fracking") uses large amounts of water (a total of about 9000 to 30,000 m^3 per well, mixed with a number of chemicals), of which a part returns to the surface (Rozell and Reaven, 2012). Fracking is suspected to lead to pollution of the overlying freshwater aquifer or surface waters, but appropriate observations and peer-reviewed studies are still lacking (Jackson et al., 2013). Densification of urban areas to reduce traffic emissions is in conflict with providing additional open space for inundation in case of floods (Hamin and Gurran, 2009).

3.7.2.2. Impact of Water Management on Climate Change Mitigation

A number of water management decisions affect GHG emissions. Water demand management has a significant impact on energy consumption because energy is required to pump and treat water, to heat it, and to treat wastewater. For example, water supply and water treatment were responsible for 1.4% of total electricity consumption in Japan in 2008 (MLIT, 2011). In the USA, total water-related energy consumption was equivalent to 13% of total electricity production in 2005, with 70% for water heating, 14% for wastewater treatment, and only 5% for pumping of irrigation water (Griffiths-Sattenspiel and Wilson, 2009). In China, where agriculture accounts for 62% of water withdrawals, groundwater pumping for irrigation accounted for only 0.6% of China's GHG emissions in 2006, a small fraction of the 17 to 20% share of agriculture as a whole (Wang et al., 2012). Where climate change reduces water resources in dry regions, desalination of seawater as an adaptation option is expected to increase GHG emissions if carbon-based fuels are used as energy source (McEvoy and Wilder, 2012).

In Southeast Asia, emissions due to peatland drainage contribute 1.3 to 3.1% of current global CO_2 emissions from the combustion of fossil fuels (Hooijer et al., 2010), and peatland rewetting could substantially reduce net GHG emissions (Couwenberg et al., 2010). Climate change mitigation by conservation of wetlands will also benefit water quality and biodiversity (House et al., 2010). Irrigation can increase CO_2 storage in soils by reducing water stress and so enhancing biomass production. Irrigation in semiarid California did not significantly increase soil organic carbon (Wu et al., 2008). Water management in rice paddies can reduce methane (CH_4) emissions. If rice paddies are drained at least once during the growing season, with resulting increased water withdrawals, global CH_4 emissions from rice fields could be decreased by 4.1 Tg yr^{-1} (16% around the year 2000), and nitrous oxide (N_2O) emissions would not increase significantly (Yan et al., 2009).

3.8. Research and Data Gaps

Precipitation and river discharge are systematically observed, but data records are unevenly available and unevenly distributed geographically. Information on many other relevant variables, such as soil moisture, snow depth, groundwater depth, and water quality, is particularly limited in developing countries. Relevant socioeconomic data, such as rates of surface water and groundwater withdrawal by each sector, and information on already implemented adaptations for stabilizing water supply, such as long-range diversions, are limited even in developed countries. In consequence, assessment capability is limited in general, and especially so in developing countries.

Modeling studies have shown that the adaptation of vegetation to changing climate may have large impacts on the partitioning of precipitation into evapotranspiration and runoff. This feedback should be investigated more thoroughly (see Box CC-VW).

Relatively little is known about the economic aspects of climate change impacts and adaptation options related to water resources. For example, regional damage curves need to be developed, relating the magnitudes of major water related disasters (such as intense precipitation and surface soil dryness) to the expected costs.

There is a continuing, although narrowing, mismatch between the large scales resolved by climate models and the catchment scale at which water is managed and adaptations must be implemented. Improving the spatial resolution of regional and global climate models, and the accuracy of methods for downscaling their outputs, can produce information more relevant to water management, although the robustness of regional climate projections is still constrained by the realism of GCM simulations of large-scale drivers. More computing capacity is needed to address these problems with more ensemble simulations at high spatial resolution. More research is also needed into novel ways of combining different approaches to projection of plausible changes in relevant climate variables so as to provide robust information to water managers. Robust attribution to anthropogenic climate change of hydrological changes, particularly changes in the frequency of extreme events, is similarly demanding, and further study is required to develop rigorous attribution tools that require less computation. In addition, there is a difficulty to model and interpret results obtained from applying models at different scales and with different logics to follow the future changes on water quality. Moreover, the establishment of a proper baseline to isolate the effects derived from climate change from the anthropogenic cause is a major challenge.

Interactions among socio-ecological systems are not yet well considered in most impact assessments. Particularly, there are few studies on the impacts of mitigation and adaptation in other sectors on the water sector, and conversely. A valuable advance would be to couple hydrological models, or even the land surface components of climate models, to data

on water management activities such as reservoir operations, irrigation, and urban withdrawals from surface water or groundwater.

To support adaptation by increasing reliance on groundwater and on the coordinated and combined use of groundwater and surface water, ground-based data are needed in the form of a long-term program to monitor groundwater dynamics and stored groundwater volumes. Understanding of groundwater recharge and groundwater surface water interactions, particularly by the assessment of experiences of conjunctive use of groundwater and surface water, needs to be better developed.

More studies are needed, especially in developing countries, on the impacts of climate change on water quality, and of vulnerability to and ways of adapting to those impacts.

References

Adam, J.C., A.F. Hamlet, and D.P. Lettenmaier, 2009: Implications of global climate change for snowmelt hydrology in the twenty-first century. *Hydrological Processes*, **23(7)**, 962-972.

Aguilera, H. and J.M. Murillo, 2009: The effect of possible climate change on natural groundwater recharge based on a simple model: a study of four karstic aquifers in SE Spain. *Environmental Geology*, **57(5)**, 963-974.

Alkama, R., B. Decharme, H. Douville, and A. Ribes, 2011: Trends in global and basin-scale runoff over the late twentieth century: methodological issues and sources of uncertainty. *Journal of Climate*, **24(12)**, 3000-3014.

Allen, D.M., A.J. Cannon, M.W. Toews, and J. Scibek, 2010: Variability in simulated recharge using different GCMs. *Water Resources Research*, **46**, W00F03, doi:10.1029/2009WR008932.

Anagnostopoulos, G.G., D. Koutsoyiannis, A. Christofides, A. Efstratiadis, and N. Mamassis, 2010: A comparison of local and aggregated climate model outputs with observed data. *Hydrological Sciences Journal*, **55(7)**, 1094-1110.

Andersen, H.E., B. Kronvang, S.E. Larsen, C.C. Hoffmann, T.S. Jensen, and E.K. Rasmussen, 2006: Climate-change impacts on hydrology and nutrients in a Danish lowland river basin. *Science of the Total Environment*, **365(1-3)**, 223-237.

Andrews, J., 2009: Towards 2030, Sydney's blueprint for development. *Urban World* **1(5)**, 42-47.

Arheimer, B., J. Andreasson, S. Fogelberg, H. Johnsson, C. Pers, and K. Persson, 2005: Climate change impact on water quality: Model results from southern Sweden. *Ambio*, **34(7)**, 559-566.

Arkell, B., 2011a: *Climate Change Implications for Water Treatment: Overview Report*. UK Water Industry Research, London, UK, 65 pp.

Arkell, B., 2011b: *Climate Change Modelling for Sewerage Networks*. UK Water Industry Research, London, UK, 31 pp.

Arndt, D.S., M.O. Baringer, and M.R. Johnson (eds.), 2010: State of the climate in 2009. *Bulletin of the American Meteorological Society*, **91(7)**, S1-S224.

Arnell, N.W., 2011: Incorporating climate change into water resources planning in England and Wales. *Journal of the American Water Resources Association*, **47(3)**, 541-549.

Arnell, N.W. and S.N. Gosling, 2013: The impacts of climate change on river flow regimes at the global scale. *Journal of Hydrology*, **486**, 351-364.

Arnell, N.W., D.P. van Vuuren, and M. Isaac, 2011: The implications of climate policy for the impacts of climate change on global water resources. *Global Environmental Change: Human and Policy Dimensions*, **21(2)**, 592-603.

Arnell, N.W., J.A. Lowe, S. Brown, S.N. Gosling, P. Gottschalk, J. Hinkel, B. Lloyd-Hughes, R.J. Nicholls, T.J. Osborn, T.M. Osborne, G.A. Rose, P. Smith, and R.F. Warren, 2013: A global assessment of the effects of climate policy on the impacts of climate change. *Nature Climate Change*, **3(5)**, 512-519.

Auld, H., D. MacIver, and J. Klaassen, 2004: Heavy rainfall and waterborne disease outbreaks: the Walkerton example. *Journal of Toxicology and Environmental Health*, *Part A: Current Issues*, **67(20-22)**, 1879-1887.

Badjeck, M., E.H. Allison, A.S. Halls, and N.K. Dulvy, 2010: Impacts of climate variability and change on fishery-based livelihoods. *Marine Policy*, **34(3)**, 375-383.

Bae, D., I. Jung, and D.P. Lettenmaier, 2011: Hydrologic uncertainties in climate change from IPCC AR4 GCM simulations of the Chungju basin, Korea. *Journal of Hydrology*, **401(1-2)**, 90-105.

Bahri, A., 2009: *Managing the Other Side of the Water Cycle: Making Wastewater an Asset*. Global Water Partnership Technical Committee (TEC) Background Paper No.13, Global Water Partnership (GWP) Secretariat, Stockholm, Sweden, 62 pp.

Baraer, M., B.G. Mark, J.M. McKenzie, T. Condom, J. Bury, K. Huh, C. Portocarrero, J. Gomez, and S. Rathay, 2012: Glacier recession and water resources in Peru's Cordillera Blanca. *Journal of Glaciology*, **58(207)**, 134-150.

Barnett, J. and W.N. Adger, 2007: Climate change, human security and violent conflict. *Political Geography*, **26(6)**, 639-655.

Barredo, J.I., 2009: Normalised flood losses in Europe: 1970-2006. *Natural Hazards and Earth System Sciences*, **9(1)**, 97-104.

Barrios, J.E., J.A. Rodríguez-Pineda, and M.D. Benignos, 2009: Integrated river basin management in the Conchos River basin, Mexico: a case study of freshwater climate change adaptation. *Climate and Development*, **1(3)**, 249-260.

Barthel, R., S. Janisch, D. Nickel, A. Trifkovic, and T. Hoerhan, 2010: Using the multi-actor-approach in Glowa-Danube to simulate decisions for the water supply sector under conditions of global climate change. *Water Resources Management*, **24(2)**, 239-275.

Bates, B.C., Z.W. Kundzewicz, S. Wu, and J.P. Palutikof (eds.), 2008: *Climate Change and Water*. Intergovernmental Panel on Climate Change (IPCC) Technical Paper VI, IPCC Secretariat, Geneva, Switzerland, 210 pp.

Beniston, M., 2012: Impacts of climatic change on water and associated economic activities in the Swiss Alps. *Journal of Hydrology*, **412**, 291-296.

Benítez-Gilabert, M., M. Alvarez-Cobelas, and D.G. Angeler, 2010: Effects of climatic change on stream water quality in Spain. *Climatic Change*, **103(3)**, 339-352.

Benito, G. and M.J. Machado, 2012: Floods in the Iberian Peninsula. In: *Changes in Flood Risk in Europe* [Kundzewicz, Z.W. (ed.)]. CRC Press, Wallingford, UK, pp. 372-383.

Berg, P., C. Moseley, and J.O. Haerter, 2013: Strong increase in convective precipitation in response to higher temperatures. *Nature Geoscience*, **6(3)**, 181-185.

Bergsma, E., J. Gupta, and P. Jong, 2012: Does individual responsibility increase the adaptive capacity of society? The case of local water management in the Netherlands. *Resources Conservation and Recycling*, **64**, 13-22.

Beyene, T., D.P. Lettenmaier, and P. Kabat, 2010: Hydrologic impacts of climate change on the Nile River basin: implications of the 2007 IPCC scenarios. *Climatic Change*, **100(3-4)**, 433-461.

Bhutiyani, M.R., V.S. Kale, and N.J. Pawar, 2008: Changing streamflow patterns in the rivers of northwestern Himalaya: implications of global warming in the 20th century. *Current Science*, **95(5)**, 618-626.

Biemans, H., L. Speelman, F. Ludwig, E. Moors, A.J. Wiltshire, P. Kumar, D. Gerten, and P. Kabat, 2013: Future water resources for food production in five South Asian river basins and potential of adaptation options – a modeling study. *Science of the Total Environment* (in press), doi:10.1016/j.scitotenv.2013.05.092.

Black, M. and J. King, 2009: *The Atlas of Water: Mapping the World's Most Critical Resource*. 2nd edn., University of California Press, Berkeley, CA, USA, 128 pp.

Blöschl, G. and A. Montanari, 2010: Climate change impacts-throwing the dice? *Hydrological Processes*, **24(3)**, 374-381.

Bolch, T., A. Kulkarni, A. Kaab, C. Huggel, F. Paul, J.G. Cogley, H. Frey, J.S. Kargel, K. Fujita, M. Scheel, S. Bajracharya, and M. Stoffel, 2012: The state and fate of Himalayan glaciers. *Science*, **336(6079)**, 310-314.

Bonte, M. and J.J.G. Zwolsman, 2010: Climate change induced salinisation of artificial lakes in the Netherlands and consequences for drinking water production. *Water Research*, **44(15)**, 4411-4424.

Bourne, C.M., D.G. Kehler, Y.F. Wiersma, and D. Cote, 2011: Barriers to fish passage and barriers to fish passage assessments: the impact of assessment methods and assumptions on barrier identification and quantification of watershed connectivity. *Aquatic Ecology*, **45(3)**, 389-403.

Bouwer, L.M., 2011: Have disaster losses increased due to anthropogenic climate change? *Bulletin of the American Meteorological Society*, **92(1)**, 39-46.

Bouwer, L.M., 2013: Projections of future extreme weather losses under changes in climate and exposure. *Risk Analysis*, **33(5)**, 915-930.

Bowes, M.J., E. Gozzard, A.C. Johnson, P.M. Scarlett, C. Roberts, D.S. Read, L.K. Armstrong, S.A. Harman, and H.D. Wickham, 2012: Spatial and temporal changes in chlorophyll-a concentrations in the River Thames basin, UK: are phosphorus concentrations beginning to limit phytoplankton biomass? *Science of the Total Environment*, **426**, 45-55.

Boxall, A.B.A., A. Hardy, S. Beulke, T. Boucard, L. Burgin, P.D. Falloon, P.M. Haygarth, T. Hutchinson, R.S. Kovats, G. Leonardi, L.S. Levy, G. Nichols, S.A. Parsons, L. Potts, D. Stone, E. Topp, D.B. Turley, K. Walsh, E.M.H. Wellington, and R.J. Williams, 2009: Impacts of climate change on indirect human exposure to pathogens and chemicals from agriculture. *Environmental Health Perspectives*, **117(4)**, 508-514.

Brauman, K.A., S. Siebert, and J.A. Foley, 2013: Improvements in crop water productivity increase water sustainability and food security-a global analysis. *Environmental Research Letters*, **8(2)**, 024030, doi:10.1088/1748-9326/8/2/024030.

Brekke, L.D., M.D. Dettinger, E.P. Maurer, and M. Anderson, 2008: Significance of model credibility in estimating climate projection distributions for regional hydroclimatological risk assessments. *Climatic Change*, **89(3-4)**, 371-394.

Brekke, L.D., J.E. Kiang, J.R. Olsen, R.S. Pulwarty, D.A. Raff, D.P. Turnipseed, R.S. Webb, and K.D. White, 2009a: *Climate Change and Water Resources Management – A Federal Perspective*. USGS Circular 133, U.S. Geological Survey (USGS), Reston, VA, USA, 65 pp.

Brekke, L.D., E.P. Maurer, J.D. Anderson, M.D. Dettinger, E.S. Townsley, A. Harrison, and T. Pruitt, 2009b: Assessing reservoir operations risk under climate change. *Water Resources Research*, **45**, W04411, doi:10.1029/2008WR00694.

Brikowski, T.H., 2008: Doomed reservoirs in Kansas, USA? Climate change and groundwater mining on the Great Plains lead to unsustainable surface water storage. *Journal of Hydrology*, **354(1-4)**, 90-101.

Brooks, J.P., A. Adeli, J.J. Read, and M.R. McLaughlin, 2009: Rainfall simulation in greenhouse microcosms to assess bacterial-associated runoff from land-applied poultry litter. *Journal of Environmental Quality*, **38(1)**, 218-229.

Browning-Aiken, A., B. Morehouse, A. Davis, M. Wilder, R. Varady, D. Goodrich, R. Carter, D. Moreno, and E.D. McGovern, 2007: Climate, water management, and policy in the San Pedro basin: results of a survey of Mexican stakeholders near the U.S.-Mexico border. *Climatic Change*, **85(3-4)**, 323-341.

Bruno, M.C., B. Maiolini, M. Carolli, and L. Silveri, 2009: Impact of hydropeaking on hyporheic invertebrates in an Alpine stream (Trentino, Italy). *Annales De Limnologie – International Journal of Limnology*, **45(3)**, 157-170.

Buhaug, H., N.P. Gleditsch, and O.M. Theisen, 2010: Implications of climate change for armed conflict. In: *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World* [Mearns, R. and A. Norton (eds.)]. The World Bank, Washington DC, USA, pp. 75-102.

Burke, M.B., E. Miguel, S. Satyanath, J.A. Dykema, and D.B. Lobell, 2009: Warming increases the risk of civil war in Africa. *Proceedings of the National Academy of Sciences of the United States of America*, **106(49)**, 20670-20674.

Burn, D.H., M. Sharif, and K. Zhang, 2010: Detection of trends in hydrological extremes for Canadian watersheds. *Hydrological Processes*, **24(13)**, 1781-1790.

Burton, I., 2008: Climate change and the adaptation deficit. In: *The Earthscan Reader on Adaptation to Climate Change* [Lisa, E., F. Schipper, and I. Burton (eds.)]. Routledge, London, UK, pp. 89-95.

Bussi, G., X. Rodríguez-Lloveras, F. Francés, G. Benito, Y. Sánchez-Moya, and A. Sopeña, 2013: Sediment yield model implementation based on check dam infill stratigraphy in a semiarid Mediterranean catchment. *Hydrology and Earth System Sciences*, **17**, 3339-3354.

Butscher, C. and P. Huggenberger, 2009: Modeling the temporal variability of karst groundwater vulnerability, with implications for climate change. *Environmental Science and Technology*, **43(6)**, 1665-1669.

Campbell, A., A. Chenery, L. Coad, V. Kapos, F. Kershaw, J. Scharlemann, and B. Dickson, 2008: *The Linkages between Biodiversity and Climate Change Mitigation: A Review of the Recent Scientific Literature*. United Nations Environment Programme World Conservation Monitoring Centre, Cambridge, UK, 61 pp.

Carneiro, J.F., M. Boughriba, A. Correia, Y. Zarhloule, A. Rimi, and B. El Houadi, 2010: Evaluation of climate change effects in a coastal aquifer in Morocco using a density-dependent numerical model. *Environmental Earth Sciences*, **61(2)**, 241-252.

Cayan, D.R., S.A. Kammerdiener, M.D. Dettinger, J.M. Caprio, and D.H. Peterson, 2001: Changes in the onset of spring in the western United States. *Bulletin of the American Meteorological Society*, **82(3)**, 399-415.

Chakraborti, D., B. Das, and M.T. Murrill, 2011: Examining India's groundwater quality management. *Environmental Science and Technology*, **45(1)**, 27-33.

Chang, H., 2004: Water quality impacts of climate and land use changes in southeastern Pennsylvania. *Professional Geographer*, **56(2)**, 240-257.

Chang, H., J. Franczyk, and C. Kim, 2009: What is responsible for increasing flood risks? The case of Gangwon Province, Korea. *Natural Hazards*, **48(3)**, 339-354.

Changnon, S.A., 1969: Recent studies of urban effects on precipitation in the United States. *Bulletin of the American Meteorological Society*, **50(6)**, 411-421.

Chen, C., J.O. Haerter, S. Hagemann, and C. Piani, 2011: On the contribution of statistical bias correction to the uncertainty in the projected hydrological cycle. *Geophysical Research Letters*, **38(20)**, L20403, doi:10.1029/2011GL049318.

Chen, G., H. Tian, C. Zhang, M. Liu, W. Ren, W. Zhu, A.H. Chappelka, S.A. Prior, and G.B. Lockaby, 2012: Drought in the Southern United States over the 20th century: variability and its impacts on terrestrial ecosystem productivity and carbon storage. *Climatic Change*, **114(2)**, 379-397.

Chen, J., F.P. Brissette, and R. Leconte, 2011: Uncertainty of downscaling method in quantifying the impact of climate change on hydrology. *Journal of Hydrology*, **401(3-4)**, 190-202.

Chiew, F.H.S., J. Teng, J. Vaze, D.A. Post, J.M. Perraud, D.G.C. Kirono, and N.R. Viney, 2009: Estimating climate change impact on runoff across southeast Australia: method, results, and implications of the modeling method. *Water Resources Research*, **45(10)**, W10414, doi:10.1029/2008WR007338.

Chisholm, R.A., 2010: Trade-offs between ecosystem services: water and carbon in a biodiversity hotspot. *Ecological Economics*, **69(10)**, 1973-1987.

Christierson, B.V., J. Vidal, and S.D. Wade, 2012: Using UKCP09 probabilistic climate information for UK water resource planning. *Journal of Hydrology*, **424**, 48-67.

Cloke, H.L., C. Jeffers, F. Wetterhall, T. Byrne, J. Lowe, and F. Pappenberger, 2010: Climate impacts on river flow: projections for the Medway catchment, UK, with UKCP09 and CATCHMOD. *Hydrological Processes*, **24(24)**, 3476-3489.

Clow, D.W., 2010: Changes in the timing of snowmelt and streamflow in Colorado: a response to recent warming. *Journal of Climate*, **23(9)**, 2293-2306.

Collins, D.N., 2008: Climatic warming, glacier recession and runoff from Alpine basins after the Little Ice Age maximum. *Annals of Glaciology*, **48(1)**, 119-124.

Connell-Buck, C.R., J. Medellin-Azuara, J.R. Lund, and K. Madani, 2011: Adapting California's water system to warm vs. dry climates. *Climatic Change*, **109**, 133-149.

Conway, D., A. Persechino, S. Ardoin-Bardin, H. Hamandawana, C. Dieulin, and G. Mahe, 2009: Rainfall and water resources variability in Sub-Saharan Africa during the twentieth century. *Journal of Hydrometeorology*, **10(1)**, 41-59.

Cooley, H., 2008: Water management in a changing climate. In: *The World's Water 2008-2009: The Biennial Report on Freshwater Resources* [Gleick, P.H. (ed.)]. Island Press, Washington DC, USA, pp. 39-56.

Couwenberg, J., R. Dommain, and H. Joosten, 2010: Greenhouse gas fluxes from tropical peatlands in south-east Asia. *Global Change Biology*, **16(6)**, 1715-1732.

Crosbie, R.S., T. Pickett, F.S. Mpelasoka, G. Hodgson, S.P. Charles, and O.V. Barron, 2013a: An assessment of the climate change impacts on groundwater recharge at a continental scale using a probabilistic approach with an ensemble of GCMs. *Climatic Change*, **117(1-2)**, 41-53.

Crosbie, R.S., B.R. Scanlon, F.S. Mpelasoka, R.C. Reedy, J.B. Gates, and L. Zhang, 2013b: Potential climate change effects on groundwater recharge in the High Plains Aquifer, USA. *Water Resources Research*, **49(7)**, 3936-3951.

Cruz, R.V., H. Harasawa, M. Lal, S. Wu, Y. Anokhin, B. Punsalmaa, Y. Honda, M. Jafari, C. Li, and N. Huu Ninh, 2007: Asia. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 469-506.

Cunderlik, J.M. and T.B.M.J. Ouarda, 2009: Trends in the timing and magnitude of floods in Canada. *Journal of Hydrology*, **375(3-4)**, 471-480.

Cunderlik, J.M. and S.P. Simonovic, 2007: Inverse flood risk modelling under changing climatic conditions. *Hydrological Processes*, **21(5)**, 563-577.

Curriero, F., J. Patz, J. Rose, and S. Lele, 2001: The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948-1994. *American Journal of Public Health*, **91(8)**, 1194-1199.

Dahlke, H.E., S.W. Lyon, J.R. Stedinger, G. Rosqvist, and P. Jansson, 2012: Contrasting trends in floods for two sub-arctic catchments in northern Sweden–does glacier presence matter? *Hydrology and Earth System Sciences*, **16(7)**, 2123-2141.

Dai, A. 2013: Increasing drought under global warming in observations and models. *Nature Climate Change*, **3**, 52-58.

Dai, A., T. Qian, K.E. Trenberth, and J.D. Milliman, 2009: Changes in continental freshwater discharge from 1948 to 2004. *Journal of Climate*, **22(10)**, 2773-2792.

Dai, S.B., X.X. Lu, S.L. Yang, and A.M. Cai, 2008: A preliminary estimate of human and natural contributions to the decline in sediment flux from the Yangtze River to the East China Sea. *Quaternary International*, **186(1)**, 43-54.

Dankers, R., N.W. Arnell, D.B. Clark, P. Falloon, B.M. Fekete, S.N. Gosling, J. Heinke, H. Kim, Y. Masaki, Y. Satoh, and T. Stacke, 2013: First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble. *Proceedings of the National Academy of Sciences of the United States of America* (in press), doi:10.1073/pnas.1302078110.

de Graaf, R. and R.V. der Brugge, 2010: Transforming water infrastructure by linking water management and urban renewal in Rotterdam. *Technological Forecasting and Social Change*, **77(8)**, 1282-1291.

Dembo, R., 2010: Why refitting buildings is key to reducing emission. *Urban World* **1(5)**, 34-37.

de Rham, L.P., T.D. Prowse, and B.R. Bonsal, 2008: Temporal variations in river-ice break-up over the Mackenzie River basin, Canada. *Journal of Hydrology*, **349(3-4)**, 441-454.

Dessai, S., M. Hulme, R. Lempert, and R. Pielke, 2009: Climate prediction: a limit to adaptation? In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, W.N., I. Lorenzoni, and K.L. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK, pp. 64-78.

Dillon, P.J. and B. Jiménez, 2008: Water reuse via aquifer recharge: intentional and unintentional practices. In: *Water Reuse: An International Survey of Current Practice, Issues and Needs* [Jiménez, B. and T. Asano (eds.)]. IWA Publishing, London, UK, pp. 260-280.

Döll, P., 2009: Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. *Environmental Research Letters*, **4(3)**, 035006, doi:10.1088/1748-9326/4/3/035006.

Döll, P. and H. Müller Schmied, 2012: How is the impact of climate change on river flow regimes related to the impact on mean annual runoff? A global-scale analysis. *Environmental Research Letters*, **7**, 014037, doi:10.1088/1748-9326/7/1/014037.

Döll, P. and J. Zhang, 2010: Impact of climate change on freshwater ecosystems: a global-scale analysis of ecologically relevant river flow alterations. *Hydrology and Earth System Sciences*, **14(5)**, 783-799.

Donohue, R.J., M.L. Roderick, and T.R. McVicar, 2011: Assessing the differences in sensitivities of runoff to changes in climatic conditions across a large basin. *Journal of Hydrology*, **406(3-4)**, 234-244.

Ducharne, A., 2008: Importance of stream temperature to climate change impact on water quality. *Hydrology and Earth System Sciences*, **12(3)**, 797-810.

Earman, S., A.R. Campbell, F.M. Phillips, and B.D. Newman, 2006: Isotopic exchange between snow and atmospheric water vapor: estimation of the snowmelt component of groundwater recharge in the southwestern United States. *Journal of Geophysical Research: Atmospheres*, **111(D9)**, D09302, doi:10.1029/2005JD006470.

Elliott, M., A. Armstrong, J. Lobuglio, and J. Bartram, 2011: *Technologies for Climate Change Adaptation: The Water Sector* [De Lopez, T. (ed.)]. TNA Guidebook Series, UNEP Risø Centre, Roskilde, Denmark, 114 pp.

Emelko, M.B., U. Silins, K.D. Bladon, and M. Stone, 2011: Implications of land disturbance on drinking water treatability in a changing climate: demonstrating the need for "source water supply and protection" strategies. *Water Research*, **45(2)**, 461-472.

Engle, N.L. and M.C. Lemos, 2010: Unpacking governance: Building adaptive capacity to climate change of river basins in Brazil. *Global Environmental Change: Human and Policy Dimensions*, **20(1)**, 4-13.

European Communities, 2009: *Guidance Document No. 24: River Basin Management in a Changing Climate*. Common Implementation Strategy for the Water Framework Directive (2000/60/EC), Technical Report-2009-040, European Communities, Luxembourg, Luxembourg, 134 pp.

Evans, C.D., D.T. Monteith, and D.M. Cooper, 2005: Long-term increases in surface water dissolved organic carbon: observations, possible causes and environmental impacts. *Environmental Pollution*, **137(1)**, 55-71.

Falloon, P.D. and R.A. Betts, 2006: The impact of climate change on global river flow in HadGEM1 simulations. *Atmospheric Science Letters*, **7(3)**, 62-68.

Falloon, P.D. and R.A. Betts, 2010: Climate impacts on European agriculture and water management in the context of adaptation and mitigation – the importance of an integrated approach. *Science of the Total Environment*, **408(23)**, 5667-5687.

Falloon, P., R. Betts, A. Wiltshire, R. Dankers, C. Mathison, D. McNeall, P. Bates, and M. Trigg, 2011: Validation of river flows in HadGEM1 and HadCM3 with the TRIP river flow model. *Journal of Hydrometeorology*, **12(6)**, 1157-1180.

Favis-Mortlock, D. and J. Boardman, 1995: Nonlinear responses of soil-erosion to climate-change – a modeling study on the UK south-downs. *Catena*, **25(1-4)**, 365-387.

Ferguson, G. and T. Gleeson, 2012: Vulnerability of coastal aquifers to groundwater use and climate change. *Nature Climate Change*, **2**, 342-345.

Ferguson, I.M. and R.M. Maxwell, 2010: Role of groundwater in watershed response and land surface feedbacks under climate change. *Water Resources Research*, **46**, W00F02, doi:10.1029/2009WR008616.

Fernandez, R.A., J.B. Anderson, J.S. Wellner, and B. Hallet, 2011: Timescale dependence of glacial erosion rates: a case study of Marinelli Glacier, Cordillera Darwin, southern Patagonia. *Journal of Geophysical Research: Earth Surface*, **116(1)**, F01020, doi:10.1029/2010JF001685.

Feyen, L., R. Dankers, K. Bodis, P. Salamon, and J.I. Barredo, 2012: Fluvial flood risk in Europe in present and future climates. *Climatic Change*, **112(1)**, 47-62.

Ficke, A.D., C.A. Myrick, and L.J. Hansen, 2007: Potential impacts of global climate change on freshwater fisheries. *Reviews in Fish Biology and Fisheries*, **17(4)**, 581-613.

Finger, R., W. Hediger, and S. Schmid, 2011: Irrigation as adaptation strategy to climate change – a biophysical and economic appraisal for Swiss maize production. *Climatic Change*, **105(3-4)**, 509-528.

Fischer, T., M. Gemmer, L. Liu, and B. Su, 2011: Temperature and precipitation trends and dryness/wetness pattern in the Zhujiang River basin, south China, 1961-2007. *Quaternary International*, **244(2)**, 138-148.

Fischer, T., C. Menz, B. Su, and T. Scholten, 2013: Simulated and projected climate extremes in the Zhujiang River basin, south China, using the regional climate model COSMO-CLM. *International Journal of Climatology*, **33**, 2988-3001.

Flörke, M., I. Baerlund, and E. Kynast, 2012: Will climate change affect the electricity production sector? A European study. *Journal of Water and Climate Change*, **3(1)**, 44-54.

Fowler, H.J. and C.G. Kilsby, 2007: Using regional climate model data to simulate historical and future river flows in northwest England. *Climatic Change*, **80(3-4)**, 337-367.

Fowler, H.J., S. Blenkinsop, and C. Tebaldi, 2007: Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. *International Journal of Climatology*, **27(12)**, 1547-1578.

Freas, K., B. Bailey, A. Munevar, and S. Butler, 2008: Incorporating climate change in water planning. *Journal American Water Works Association*, **100(6)**, 92-99.

Fu, G., S.P. Charles, and J. Yu, 2009: A critical overview of pan evaporation trends over the last 50 years. *Climatic Change*, **97(1-2)**, 193-214.

Fu, G., S.P. Charles, F.H.S. Chiew, J. Teng, H. Zheng, A.J. Frost, W. Liu, and S. Kirshner, 2013: Modelling runoff with statistically downscaled daily site, gridded and catchment rainfall series. *Journal of Hydrology*, **492**, 254-265.

Fujihara, Y., K. Tanaka, T. Watanabe, T. Nagano, and T. Kojiri, 2008a: Assessing the impacts of climate change on the water resources of the Seyhan River basin in Turkey: use of dynamically downscaled data for hydrologic simulations. *Journal of Hydrology*, **353(1-2)**, 33-48.

Fujihara, Y., S.P. Simonovic, F. Topaloglu, K. Tanaka, and T. Watanabe, 2008b: An inverse-modelling approach to assess the impacts of climate change in the Seyhan River basin, Turkey. *Hydrological Sciences Journal*, **53(6)**, 1121-1136.

Fujita, K., A. Sakai, S. Takenaka, T. Nuimura, A.B. Surazakov, T. Sawagaki, and T. Yamanokuchi, 2013: Potential flood volume of Himalayan glacial lakes. *Natural Hazards and Earth System Sciences*, **13(7)**, 1827-1839.

Fung, F., A. Lopez, and M. New, 2011: Water availability in +2 degrees C and +4 degrees C worlds. *Philosophical Transactions of the Royal Society A*, **369(1934)**, 99-116.

Gardelle, J., Y. Arnaud, and E. Berthier, 2011: Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009. *Global and Planetary Change*, **75(1-2)**, 47-55.

Gardner, A.S., G. Moholdt, J.G. Cogley, B. Wouters, A.A. Arendt, J. Wahr, E. Berthier, R. Hock, W.T. Pfeffer, G. Kaser, S.R.M. Ligtenberg, T. Bolch, M.J. Sharp, J.O. Hagen, M.R. van den Broeke, and F. Paul, 2013: A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. *Science*, **340(6134)**, 852-857.

Gascuel-Odoux, C., P. Aurousseau, P. Durand, L. Ruiz, and J. Molenat, 2010: The role of climate on inter-annual variation in stream nitrate fluxes and concentrations. *Science of the Total Environment*, **408(23)**, 5657-5666.

Gemmer, M., T. Fischer, T. Jiang, B. Su, and L.L. Liu, 2011: Trends in precipitation extremes in the Zhujiang River basin, South China. *Journal of Climate*, **24(3)**, 750-761.

Gerbens-Leenes, P.W., A.R. van Lienden, A.Y. Hoekstra, and T.H. van der Meer, 2012: Biofuel scenarios in a water perspective: the global blue and green water footprint of road transport in 2030. *Global Environmental Change: Human and Policy Dimensions*, **22(3)**, 764-775.

Gersonius, B., R. Ashley, A. Pathirana, and C. Zevenbergen, 2013: Climate change uncertainty: building flexibility into water and flood risk infrastructure. *Climatic Change*, **116(2)**, 411-423.

Gerten, D., S. Rost, W. von Bloh, and W. Lucht, 2008: Causes of change in 20th century global river discharge. *Geophysical Research Letters*, **35(20)**, L20405, doi:10.1029/2008GL035258.

Gerten, D., J. Heinke, H. Hoff, H. Biemans, M. Fader, and K. Waha, 2011: Global water availability and requirements for future food production. *Journal of Hydrometeorology*, **12(5)**, 885-899.

Gerten, D., W. Lucht, S. Ostberg, J. Heinke, M. Kowarsch, H. Kreft, Z.W. Kundzewicz, J. Rastgooy, R. Warren, and H.J. Schellnhuber, 2013: Asynchronous exposure to global warming: freshwater resources and terrestrial ecosystems. *Environmental Research Letters*, **8(3)**, 034032, doi:10.1088/1748-9326/8/3/034032.

Giuntoli, I., B. Renard, and M. Lang, 2012: Floods in France. In: *Changes in Flood Risk in Europe* [Kundzewicz, Z.W. (ed.)]. CRC Press, Wallingford, UK, pp. 199-211.

Goderniaux, P., S. Brouyere, S. Blenkinsop, A. Burton, H.J. Fowler, P. Orban, and A. Dassargues, 2011: Modeling climate change impacts on groundwater resources using transient stochastic climatic scenarios. *Water Resources Research*, **47(12)**, W12516, doi:10.1029/2010WR010082.

Godfrey, S., P. Labhasetwar, S. Wate, and B. Jimenez, 2010: Safe greywater reuse to augment water supply and provide sanitation in semi-arid areas of rural India. *Water Science and Technology*, **62(6)**, 1296-1303.

Golombek, R., S.A.C. Kittelsen, and I. Haddeland, 2012: Climate change: impacts on electricity markets in Western Europe. *Climatic Change*, **113(2)**, 357-370.

Gosling, S.N. and N.W. Arnell, 2013: A global assessment of the impact of climate change on water scarcity. *Climatic Change*, 15 pp. **(**in press**),** doi:10.1007/s10584-013-0853-x.

Gosling, S.N., D. Bretherton, K. Haines, and N.W. Arnell, 2010: Global hydrology modelling and uncertainty: running multiple ensembles with a campus grid. *Philosophical Transactions of the Royal Society A*, **368(1926)**, 4005-4021.

Goulden, M., D. Conway, and A. Persechino, 2009: Adaptation to climate change in international river basins in Africa: a review. *Hydrological Sciences Journal*, **54(5)**, 805-828.

Green, T.R., M. Taniguchi, H. Kooi, J.J. Gurdak, D.M. Allen, K.M. Hiscock, H. Treidel, and A. Aureli, 2011: Beneath the surface of global change: impacts of climate change on groundwater. *Journal of Hydrology*, **405(3-4)**, 532-560.

Griffiths-Sattenspiel, B. and W. Wilson, 2009: *The Carbon Footprint of Water*. A River Network Report, River Network, Portland, OR, USA, 49 pp.

Grosse, G., V. Romanovsky, T. Jorgenson, K.W. Anthony, J. Brown, and P.P. Overduin, 2011: Vulnerability and feedbacks of permafrost to climate change. *Eos, Transactions American Geophysical Union*, **92(9)**, 73-74.

Gujja, B., S. Dalai, H. Shaik, and V. Goud, 2009: Adapting to climate change in the Godavari River basin of India by restoring traditional water storage systems. *Climate and Development*, **1(3)**, 229-240.

Gunkel, G., 2009: Hydropower – a green energy? Tropical reservoirs and greenhouse gas emissions. *Clean – Soil, Air, Water*, **37(9)**, 726-734.

Gupta, A., K.V. Bharadwaj, S. Lama, and J. Mathur, 2010: Energy analysis of irrigated jetropha cultivation for producing biodiesel. *Low Carbon Economy*, **1**, 54-60.

Hagemann, S., C. Chen, J.O. Haerter, J. Heinke, D. Gerten, and C. Piani, 2011: Impact of a statistical bias correction on the projected hydrological changes obtained from three GCMs and two hydrology models. *Journal of Hydrometeorology*, **12(4)**, 556-578.

Hagemann, S., C. Chen, D.B. Clark, S. Folwell, S.N. Gosling, I. Haddeland, N. Hanasaki, J. Heinke, F. Ludwig, F. Voß, and A.J. Wiltshire, 2013: Climate change impact on available water resources obtained using multiple global climate and hydrology models. *Earth System Dynamics*, **4**, 129-144.

Hall, J., 2007: Probabilistic climate scenarios may misrepresent uncertainty and lead to bad adaptation decisions. *Hydrological Processes*, **21(8)**, 1127-1129.

Hall, J. and C. Murphy, 2010: Vulnerability analysis of future public water supply under changing climate conditions: a study of the Moy Catchment, western Ireland. *Water Resources Management*, **24(13)**, 3527-3545.

Hall, J.W., G. Watts, M. Keil, L. de Vial, R. Street, K. Conlan, P.E. O'Connell, K.J. Beven, and C.G. Kilsby, 2012: Towards risk-based water resources planning in England and Wales under a changing climate. *Water and Environment Journal*, **26(1)**, 118-129.

Hamin, E.M. and N. Gurran, 2009: Urban form and climate change: balancing adaptation and mitigation in the US and Australia. *Habitat International*, **33(3)**, 238-245.

Hanasaki, N., S. Fujimori, T. Yamamoto, S. Yoshikawa, Y. Masaki, Y. Hijioka, M. Kainuma, Y. Kanamori, T. Masui, K. Takahashi, and S. Kanae, 2013: A global water scarcity assessment under Shared Socio-economic Pathways – part 2: water availability and scarcity. *Hydrology and Earth System Sciences*, **17**, 2393-2413.

Handmer, J., Y. Honda, Z.W. Kundzewicz, N. Arnell, G. Benito, J. Hatfield, I.F. Mohamed, P. Peduzzi, S. Wu, B. Sherstyukov, K. Takahashi, and Z. Yan, 2012: Changes in impacts of climate extremes: human systems and ecosystems. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, USA, pp. 231-290.

Hannaford, J. and J.W. Hall, 2012: Flood risk in the UK: evidence of change and management responses. In: *Changes in Flood Risk in Europe* [Kundzewicz, Z.W. (ed.)]. CRC Press, Wallingford, UK, pp. 344-361.

Harris, C., L.U. Arenson, H.H. Christiansen, B. Etzelmüller, R. Frauenfelder, S. Gruber, W. Haeberli, C. Hauck, M. Hoelzle, O. Humlum, K. Isaksen, A. Kääb, M.A. Kern-Lütschg, M. Lehning, N. Matsuoka, J.B. Murton, J. Noezli, M. Phillips, N. Ross, M. Seppälä, S.M. Springman, and D.V. Mühll, 2009: Permafrost and climate in Europe: monitoring and modelling thermal, geomorphological and geotechnical responses. *Earth-Science Reviews*, **92(3-4)**, 117-171.

Hattermann, F.F., Z.W. Kundzewicz, S. Huang, T. Vetter, W. Kron, O. Burghoff, B. Merz, A. Bronstert, V. Krysanova, F.-W. Gerstengarbe, P. Werner, and Y. Hauf, 2012: Flood risk from a holistic perspective – observed changes in Germany. In: *Changes in Flood Risk in Europe* [Kundzewicz, Z.W. (ed.)]. CRC Press, Wallingford, UK, pp. 212-237.

Hawkins, E. and R. Sutton, 2011: The potential to narrow uncertainty in projections of regional precipitation change. *Climate Dynamics*, **37(1-2)**, 407-418.

Hayashi, A., K. Akimoto, F. Sano, S. Mori, and T. Tomoda, 2010: Evaluation of global warming impacts for different levels of stabilization as a step toward determination of the long-term stabilization target. *Climatic Change*, **98**, 87-112.

Henderson, J., C. Rodgers, R. Jones, J. Smith, K. Strzepek, J. Martinich, 2013: Economic impacts of climate change on water resources in the coterminous United States. *Mitigation and Adaptation Strategies for Global Change*, 23 pp. (in press), doi:10.1007/s11027-013-9483-x.

Henriques, C. and G. Spraggs, 2011: Alleviating the flood risk of critical water supply sites: asset and system resilience. *Journal of Water Supply Research and Technology – Aqua*, **60(1)**, 61-68.

Hidalgo, H.G., T. Das, M.D. Dettinger, D.R. Cayan, D.W. Pierce, T.P. Barnett, G. Bala, A. Mirin, A.W. Wood, C. Bonfils, B.D. Santer, and T. Nozawa, 2009: Detection and attribution of streamflow timing changes to climate change in the western United States. *Journal of Climate*, **22(13)**, 3838-3855.

Hilker, N., A. Badoux, and C. Hegg, 2009: The Swiss flood and landslide damage database 1972-2007. *Natural Hazards and Earth System Sciences*, **9(3)**, 913-925.

Hirabayashi, Y., S. Kanae, S. Emori, T. Oki, and M. Kimoto, 2008: Global projections of changing risks of floods and droughts in a changing climate. *Hydrological Sciences Journal*, **53(4)**, 754-772.

Hirabayashi, Y., R. Mahendran, S. Koirala, L. Konoshima, D. Yamazaki, S. Watanabe, and S. Kanae, 2013: Global flood risk under climate change. *Nature Climate Change*, **3**, 816-821.

Hirsch, R.M. and K.R. Ryberg, 2012: Has the magnitude of floods across the USA changed with global CO_2 levels? *Hydrological Sciences Journal*, **57(1)**, 1-9.

Hirschi, M., S.I. Seneviratne, V. Alexandrov, F. Boberg, C. Boroneant, O.B. Christensen, H. Formayer, B. Orlowsky, and P. Stepanek, 2011: Observational evidence for soil-moisture impact on hot extremes in southeastern Europe. *Nature Geoscience*, **4(1)**, 17-21.

Hoekstra, A.Y. and J. de Kok, 2008: Adapting to climate change: a comparison of two strategies for dike heightening. *Natural Hazards*, **47(2)**, 217-228.

Holman, I.P., D. Tascone, and T.M. Hess, 2009: A comparison of stochastic and deterministic downscaling methods for modelling potential groundwater recharge under climate change in East Anglia, UK: implications for groundwater resource management. *Hydrogeology Journal*, **17(7)**, 1629-1641.

Hooijer, A., S. Page, J.G. Canadell, M. Silvius, J. Kwadijk, H. Wösten, and J. Jauhiainen, 2010: Current and future CO_2 emissions from drained peatlands in Southeast Asia. *Biogeosciences*, **7(5)**, 1505-1514.

House, J.I., H.G. Orr, J.M. Clark, A.V. Gallego-Sala, C. Freeman, I.C. Prentice, and P. Smith, 2010: Climate change and the British Uplands: evidence for decision-making. *Climate Research*, **45(1)**, 3-12.

Howard, G., K. Charles, K. Pond, A. Brookshaw, R. Hossain, and J. Bartram, 2010: Securing 2020 vision for 2030: climate change and ensuring resilience in water and sanitation services. *Journal of Water and Climate Change*, **1(1)**, 2-16.

Howden, N.J.K., T.P. Burt, F. Worrall, M.J. Whelan, and M. Bieroza, 2010: Nitrate concentrations and fluxes in the River Thames over 140 years (1868-2008): are increases irreversible? *Hydrological Processes*, **24(18)**, 2657-2662.

Hsiang, S.M., K.C. Meng, and M.A. Cane, 2011: Civil conflicts are associated with the global climate. *Nature*, **476,** 438-441.

Huard, D., 2011: A black eye for the *Hydrological Sciences Journal*. Discussion of 'A comparison of local and aggregated climate model outputs with observed data' by G.G. Anagnostopoulos *et al*. (2010, *Hydrological Sciences Journal*, **55(7)**, 1094-1110). *Hydrological Sciences Journal*, **56(7)**, 1330-1333.

Huggel, C., J.J. Clague, and O. Korup, 2012: Is climate change responsible for changing landslide activity in high mountains? *Earth Surface Processes and Landforms*, **37(1)**, 77-91.

Hughes, D.A., D.G. Kingston, and M.C. Todd, 2011: Uncertainty in water resources availability in the Okavango River basin as a result of climate change. *Hydrology and Earth System Sciences*, **15(3)**, 931-941.

Huntjens, P., C. Pahl-Wostl, and J. Grin, 2010: Climate change adaptation in European river basins. *Regional Environmental Change*, **10(4)**, 263-284.

Huntjens, P., L. Lebel, C. Pahl-Wostl, J. Camkin, R. Schulze, and N. Kranz, 2012: Institutional design propositions for the governance of adaptation to climate change in the water sector. *Global Environmental Change: Human and Policy Dimensions*, **22(1)**, 67-81.

Huss, M., 2011: Present and future contribution of glacier storage change to runoff from macroscale drainage basins in Europe. *Water Resources Research*, **47**, W07511, doi:10.1029/2010WR010299.

Immerzeel, W.W., F. Pellicciotti, and M.F.P. Bierkens, 2013: Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds. *Nature Geoscience*, **6**, 742-745.

IPCC, 2007: *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K, and A. Reisinger (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp.

Ishak, E.H., A. Rahman, S. Westra, A. Sharma, and G. Kuczera, 2010: Preliminary analysis of trends in Australian flood data. In: *World Environmental and Water Resources Congress 2010: Challenges of Change* [Palmer, R.N. (ed.)]. Proceedings of the Congress, American Society of Civil Engineers, Reston, VA, USA, pp. 115-124.

ISO, 2009: *ISO 31000: 2009 Risk Management – Principles and Guidelines*. International Organization for Standardization (ISO), Geneva, Switzerland, 24 pp.

Jackson, C.R., R. Meister, and C. Prudhomme, 2011: Modelling the effects of climate change and its uncertainty on UK Chalk groundwater resources from an ensemble of global climate model projections. *Journal of Hydrology*, **399(1-2)**, 12-28.

Jackson, R.E., A.W. Gorody, B. Mayer, J.W. Roy, M.C. Ryan, and D.R. Van Stempvoort, 2013: Groundwater protection and unconventional gas extraction: the critical need for field-based hydrogeological research. *Ground Water*, **51(4)**, 488-510.

Jacobson, M.Z., 2009: Review of solutions to global warming, air pollution, and energy security. *Energy and Environmental Science*, **2(2)**, 148-173.

Jean, J.-S., H.-R. Guo, S.-H. Chen, C.-C. Liu, W.-T. Chang, Y.-J. Yang, and M.-C. Huang, 2006: The association between rainfall rate and occurrence of an enterovirus epidemic due to a contaminated well. *Journal of Applied Microbiology*, **101(6)**, 1224-1231

Jeelani, G., 2008: Aquifer response to regional climate variability in a part of Kashmir Himalaya in India. *Hydrogeology Journal*, **16(8)**, 1625-1633.

Jiang, F., C. Zhu, G. Mu, R. Hu, and Q. Meng, 2005: Magnification of flood disasters and its relation to regional precipitation and local human activities since the 1980s in Xinjiang, northwestern China. *Natural Hazards*, **36(3)**, 307-330.

Jiang, T., Z.W. Kundzewicz, and B. Su, 2008: Changes in monthly precipitation and flood hazard in the Yangtze River basin, China. *International Journal of Climatology*, **28(11)**, 1471-1481.

Jiang, T., T. Fischer, and X.X. Lu, 2013: Larger Asian rivers: changes in hydro-climate and water environments. *Quaternary International*, **304**, 1-4.

Jiang, X.Y., G.Y. Niu, and Z.L. Yang, 2009: Impacts of vegetation and groundwater dynamics on warm season precipitation over the Central United States. *Journal of Geophysical Research: Atmospheres*, **114**, D06109, doi:10.1029/2008JD010756.

Jiménez, B.E.C., 2008: Helminths ova control in wastewater and sludge for agricultural reuse. In: *Water and Health Vol. II, Encyclopedia of Life Support Systems (EOLSS)* [Grabow, W. (ed.)]. Developed under the auspices of UNESCO, Eolss Publishers, Oxford, UK, pp. 429-449.

Jiménez, B.E.C., 2011: Safe sanitation in low economic development areas. In: *Treatise on Water Science, Vol. 4: Water-Quality Engineering* [Wilderer, P. (ed.)]. Elsevier Science and IWA Publishing, London, UK, pp. 147-200.

Jiménez, B.E.C. and T. Asano (eds.), 2008: *Water Reuse: An International Survey of Current Practice, Issues and Needs*. Scientific and Technical Report No. 20, International Water Association (IWA) Publishing, London, UK, 648 pp.

Jóhannesson, T., G. Aðalgeirsdóttir, A. Ahlstrøm, L.M. Andreassen, S. Beldring, H. Björnsson, P. Crochet, B. Einarsson, H. Elvehøy, S. Guðmundsson, R. Hock, H. Machguth, K. Melvold, F. Pálsson, V. Radić, O. Sigurðsson, and T. Thorsteinsson, 2012: Hydropower, snow and ice. In: *Climate Change and Energy Systems: Impacts, Risks and Adaptation in the Nordic and Baltic Countries* [Thorsteinsson, T. and H. Björnsson (eds.)]. Nordic Council of Ministers, Copenhagen, Denmark, pp. 91-111.

Jones, J.A., 2011: Hydrologic responses to climate change: considering geographic context and alternative hypotheses. *Hydrological Processes*, **25(12)**, 1996-2000.

Jung, I.W. and H. Chang, 2012: Climate change impacts on spatial patterns in drought risk in the Willamette River basin, Oregon, USA. *Theoretical and Applied Climatology*, **108(3-4)**, 355-371.

Kääb, A., E. Berthier, C. Nuth, J. Gardelle, and Y. Arnaud, 2012: Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas. *Nature*, **488(7412)**, 495-498.

Kalra, A., T.C. Piechota, R. Davies, and G.A. Tootle, 2008: Changes in US streamflow and western US snowpack. *Journal of Hydrologic Engineering*, **13(3)**, 156-163.

Kaser, G., M. Grosshauser, and B. Marzeion, 2010: Contribution potential of glaciers to water availability in different climate regimes. *Proceedings of the National Academy of Sciences of the United States of America*, **107(47)**, 20223-20227.

Kashaigili, J.J., K. Rajabu, and P. Masolwa, 2009: Freshwater management and climate change adaptation: experiences from the Great Ruaha River catchment in Tanzania. *Climate and Development*, **1(3)**, 220-228.

Katul, G. and Novick, K., 2009: Evapotranspiration. In: *Encyclopedia of Inland Waters* [Likens, G.E. (ed.)]. Academic Press, Waltham, MA, USA, pp. 661-667.

Keller, J., 2008: From microbial fuel cells to bio electrochemical systems: how to convert organic pollutants to electric energy and more. In: *Water and Energy Workshop, 9 September 2008 in Vienna's Austria Centre – Summary* [International Water Association (IWA) (ed.)]. IWA, London, UK, p. 10, www.iwahq.org/ContentSuite/upload/iwa/Document/2008_Vienna_Day2_01.pdf.

Kharin, V.V., F.W. Zwiers, X. Zhang, and M. Wehner, 2013: Changes in temperature and precipitation extremes in the CMIP5 ensemble. *Climatic Change*, **119(2)**, 345-357.

Kim, S., Y. Tachikawa, E. Nakakita, and K. Takara, 2009: Reconsideration of reservoir operations under climate change: case study with Yagisawa Dam, Japan. *Annual Journal of Hydraulic Engineering*, *JSCE*, **53**, 115-120.

King, C.W., M.E. Webber, and I.J. Duncan, 2010: The water needs for LDV transportation in the United States. *Energy Policy*, **38(2)**, 1157-1167.

Kingsford, R.T., 2011: Conservation management of rivers and wetlands under climate change – a synthesis. *Marine and Freshwater Research*, **62(3)**, 217-222.

Kingston, D.G. and R.G. Taylor, 2010: Sources of uncertainty in climate change impacts on river discharge and groundwater in a headwater catchment of the Upper Nile basin, Uganda. *Hydrology and Earth System Sciences*, **14(7)**, 1297-1308.

Kingston, D.G., M.C. Todd, R.G. Taylor, J.R. Thompson, and N.W. Arnell, 2009: Uncertainty in the estimation of potential evapotranspiration under climate change. *Geophysical Research Letters*, **36**, L20403, doi:10.1029/2009GL040267.

Kingston, D.G., J.R. Thompson, and G. Kite, 2011: Uncertainty in climate change projections of discharge for the Mekong River basin. *Hydrology and Earth System Sciences*, **15(5)**, 1459-1471.

Kirshen, P., 2007: *Adaptation Options and Cost in Water Supply*. United Nations Framework Convention on Climate Change, Bonn, Germany, 57 pp.

Kling, H., M. Fuchs, and M. Paulin, 2012: Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios. *Journal of Hydrology*, **424**, 264-277.

Knowles, N., M.D. Dettinger, and D.R. Cayan, 2006: Trends in snowfall versus rainfall in the western United States. *Journal of Climate*, **19(18)**, 4545-4559.

Knutson, T.R., J.L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J.P. Kossin, A.K. Srivastava, and M. Sugi, 2010: Tropical cyclones and climate change. *Nature Geoscience*, **3(3)**, 157-163.

Koboltschnig, G.R., W. Schöner, M. Zappa, and H. Holzmann, 2007: Contribution of glacier melt to stream runoff: if the climatically extreme summer of 2003 had happened in 1979. *Annals of Glaciology*, **46(1)**, 303-308.

Koetse, M.J. and P. Rietveld, 2009: The impact of climate change and weather on transport: an overview of empirical findings. *Transportation Research Part D: Transport and Environment*, **14(3)**, 205-221.

Konzmann, M., D. Gerten, and J. Heinke, 2013: Climate impacts on global irrigation requirements under 19 GCMs, simulated with a vegetation and hydrology model. *Hydrological Sciences Journal*, **58**, 1-18.

Korhonen, J. and E. Kuusisto, 2010: Long-term changes in the discharge regime in Finland. *Hydrology Research*, **41(3-4)**, 253-268.

Koutsoyiannis, D., A. Efstratiadis, N. Mamassis, and A. Christofides, 2008: On the credibility of climate predictions. *Hydrological Sciences Journal*, **53(4)**, 671-684.

Koutsoyiannis, D., A. Montanari, H.F. Lins, and T.A. Cohn, 2009: Climate, hydrology and freshwater: towards an interactive incorporation of hydrological experience into climate research. *Hydrological Sciences Journal*, **54(2)**, 394-405.

Koutsoyiannis, D., A. Christofides, A. Efstratiadis, G.G. Anagnostopoulos, and N. Mamassis, 2011: Scientific dialogue on climate: is it giving black eyes or opening closed eyes? Reply to "A black eye for the *Hydrological Sciences Journal*" by D. Huard. *Hydrological Sciences Journal*, **56(7)**, 1334-1339.

Kranz, N., T. Menniken, and J. Hinkel, 2010: Climate change adaptation strategies in the Mekong and Orange-Senqu basins: what determines the state-of-play? *Environmental Science and Policy*, **13(7)**, 648-659.

Krysanova, V., C. Dickens, J. Timmerman, C. Varela-Ortega, M. Schlueter, K. Roest, P. Huntjens, F. Jaspers, H. Buiteveld, E. Moreno, J.d.P. Carrera, R. Slamova, M. Martinkova, I. Blanco, P. Esteve, K. Pringle, C. Pahl-Wostl, and P. Kabat, 2010: Cross-comparison of climate change adaptation strategies across large river basins in Europe, Africa and Asia. *Water Resources Management*, **24(14)**, 4121-4160.

Kundzewicz, Z.W. and P. Döll, 2009: Will groundwater ease freshwater stress under climate change? *Hydrological Sciences Journal*, **54(4)**, 665-675.

Kundzewicz, Z.W. and V. Krysanova, 2010: Climate change and stream water quality in the multi-factor context. *Climatic Change*, **103(3)**, 353-362.

Kundzewicz, Z.W., L.J. Mata, N.W. Arnell, P. Döll, P. Kabat, B. Jiménez, K.A. Miller, T. Oki, Z. Sen and I.A. Shiklomanov, 2007: Freshwater resources and their management. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability*. *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 173-210.

Kundzewicz, Z.W., S. Kanae, S.I. Seneviratne, J. Handmer, N. Nicholls, P. Peduzzi, R. Mechler, L.M. Bouwer, N. Arnell, K. Mach, R. Muir-Wood, G. R. Brakenridge, W. Kron, G. Benito, Y. Honda, K. Takahashi, and B. Sherstyukov. 2013: Flood risk and climate change – global and regional perspectives. *Hydrological Sciences Journal* (in press), doi:10.1080/02626667.2013.857411.

Kustu, M.D., Y. Fan, and A. Robock, 2010: Large-scale water cycle perturbation due to irrigation pumping in the US High Plains: a synthesis of observed streamflow changes. *Journal of Hydrology*, **390(3-4)**, 222-244.

Lambert, F.H., P.A. Stott, M.R. Allen, and M.A. Palmer, 2004: Detection and attribution of changes in 20th century land precipitation. *Geophysical Research Letters*, **31(10)**, L10203, doi:10.1029/2004GL019545.

Lawler, D., G. McGregor, and I. Phillips, 2003: Influence of atmospheric circulation changes and regional climate variability on river flow and suspended sediment fluxes in southern Iceland. *Hydrological Processes*, **17(16)**, 3195-3223.

Lawrence, D. and I. Haddeland, 2011: Uncertainty in hydrological modelling of climate impacts in four Norwegian catchments. *Hydrology Research*, **42(6)**, 457-471.

Lempert, R.J. and D.G. Groves, 2010: Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west. *Technological Forecasting and Social Change*, **77(6)**, 960-974.

Lempert, R.J., M.E. Schlesinger, and S.C. Bankes, 1996: When we don't know the costs or the benefits: adaptive strategies for abating climate change. *Climatic Change*, **33(2)**, 235-274.

Lempert, R.J., D.G. Groves, S.W. Popper, and S.C. Bankes, 2006: A general, analytic method for generating robust strategies and narrative scenarios. *Management Science*, **52(4)**, 514-528.

Li, Z., W. Liu, X. Zhang, and F. Zheng, 2011: Assessing the site-specific impacts of climate change on hydrology, soil erosion and crop yields in the Loess Plateau of China. *Climatic Change*, **105(1-2)**, 223-242.

Lins, H.F. and T.A. Cohn, 2011: Stationarity: wanted dead or alive? *Journal of the American Water Resources Association*, **47(3)**, 475-480.

Little, M.G. and R.B. Jackson, 2010: Potential impacts of leakage from deep CO_2 geosequestration on overlying freshwater aquifers. *Environmental Science and Technology*, **44(23)**, 9225-9232.

Liu, C., R.P. Allan, and G.J. Huffman, 2012: Co-variation of temperature and precipitation in CMIP5 models and satellite observations. *Geophysical Research Letters*, **39**, L13803, doi:10.1029/2012GL052093.

Liu, H., 2011: Impact of climate change on groundwater recharge in dry areas: an ecohydrology approach. *Journal of Hydrology*, **407(1-4)**, 175-183.

Liu, Y., J. Zhang, G. Wang, J. Liu, R. He, H. Wang, C. Liu, and J. Jin, 2013: Assessing the effect of climate natural variability in water resources evaluation impacted by climate change. *Hydrological Processes*, **27(7)**, 1061-1071.

Loaiciga, H.A., T.J. Pingel, and E.S. Garcia, 2012: Sea water intrusion by sea-level rise: scenarios for the 21st century. *Ground Water*, **50(1)**, 37-47.

Loos, S., H. Middelkoop, M. van der Perk, and R. van Beek, 2009: Large scale nutrient modelling using globally available datasets: a test for the Rhine basin. *Journal of Hydrology*, **369(3-4)**, 403-415.

Lopez, A., F. Fung, M. New, G. Watts, A. Weston, and R.L. Wilby, 2009: From climate model ensembles to climate change impacts and adaptation: a case study of water resource management in the southwest of England. *Water Resources Research*, **45**, W08419, doi:10.1029/2008WR007499.

Lu, X.X., S. Zhang, and J. Xu, 2010: Climate change and sediment flux from the Roof of the World. *Earth Surface Processes and Landforms*, **35(6)**, 732-735.

Ludwig, F., P. Kabat, H. van Schaik, and M. van der Valk, (eds.) 2009: *Climate Change Adaptation in the Water Sector*. Earthscan, London, UK, 320 pp.

MacDonald, A.M., R.C. Carlow, D.M.J. MacDonald, W.G. Darling, and B.É.Ó. Dochartaigh, 2009: What impact will climate change have on rural groundwater supplies in Africa? *Hydrological Sciences Journal*, **54(4)**, 690-703.

Mackay, R. and E. Last, 2010: SWITCH city water balance: a scoping model for integrated urban water management. *Reviews in Environmental Science and Bio-Technology*, **9(4)**, 291-296.

Macleod, C.J.A., P.D. Falloon, R. Evans, and P.M. Haygarth, 2012: Chapter 2: The effects of climate change on the mobilization of diffuse substances from agricultural systems. In: *Advances in Agronomy, Vol. 115* [Sparks, D.L. (ed.)]. Elsevier Science and Technology/Academic Press, Waltham, MA, USA, pp. 41-77.

Madani, K. and J.R. Lund, 2010: Estimated impacts of climate warming on California's high-elevation hydropower. *Climatic Change*, **102(3-4)**, 521-538.

Mahlstein, I., R.W. Portmann, J.S. Daniel, S. Solomon, and R. Knutti, 2012: Perceptible changes in regional precipitation in a future climate. *Geophysical Research Letters*, **39**, L05701, doi:10.1029/2011GL050738.

Major, D.C., A. Omojola, M. Dettinger, R.T. Hanson, R. Sanchez-Rodriguez, 2011: Climate change, water, and wastewater in cities. In: *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, C., W.D. Solecki, S.A. Hammer, and S. Mehrotra (eds.)]. Cambridge University Press, Cambridge, UK, pp. 113-143.

Manning, L.J., J.W. Hall, H.J. Fowler, C.G. Kilsby, and C. Tebaldi, 2009: Using probabilistic climate change information from a multimodel ensemble for water resources. *Water Resources Research*, **45**, W11411, doi:10.1029/2007WR006674.

Marcé, R., M.T. Rodríguez-Arias, J.C. García, and J. Armengol, 2010: El Niño Southern Oscillation and climate trends impact reservoir water quality. *Global Change Biology*, **16(10)**, 2857-2865.

Markoff, M.S. and A.C. Cullen, 2008: Impact of climate change on Pacific Northwest hydropower. *Climatic Change*, **87(3-4)**, 451-469.

Marsalek, J., B.E. Jiménez, P.-A. Malmquist, M. Karamouz, J. Goldenfum, and B. Chocat, 2006: *Urban Water Cycle Processes and Interactions*. International Hydrological Programme, Technical Documents in Hydrology No. 78, United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris, France, 87 pp.

Marshall, E. and T. Randhir, 2008: Effect of climate change on watershed system: a regional analysis. *Climatic Change*, **89(3-4)**, 263-280.

Masterson, J.P. and S.P. Garabedian, 2007: Effects of sea-level rise on ground water flow in a coastal aquifer system. *Ground Water*, **45(2)**, 209-217.

Matthews, J.H. and A.J. Wickel, 2009: Embracing uncertainty in freshwater climate change adaptation: a natural history approach. *Climate and Development*, **1(3)**, 269-279.

McCafferty, P., 2008: Energy balances in water savings and reuse programs. In: *Water and Energy Workshop*, *9 September 2008 in Vienna's Austria Centre – Summary* [International Water Association (IWA) (ed.)]. IWA, London, UK, pp. 4-5, www.iwahq.org/ContentSuite/upload/iwa/Document/2008_Vienna_Day2_01.pdf.

McDonald, R.I. and E.H. Girvetz, 2013: Two challenges for U. S. irrigation due to climate change: increasing irrigated area in wet states and increasing irrigation rates in dry states. *Plos One*, **8(6)**, e65589, doi:10.1371/journal.pone.0065589.

McEvoy, J. and M. Wilder, 2012: Discourse and desalination: potential impacts of proposed climate change adaptation interventions in the Arizona-Sonora border region. *Global Environmental Change: Human and Policy Dimensions*, **22(2)**, 353-363.

McGuckin, R., 2008: Carbon footprints and emerging mitigation/trading regimes. In: *Water and Energy Workshop*, *9 September 2008 in Vienna's Austria Centre – Summary* [International Water Association (IWA) (ed.)]. IWA, London, UK, p. 3, www.iwahq.org/ContentSuite/upload/iwa/Document/2008_Vienna_Day2_01.pdf.

McVicar, T.R., T.G. Van Niel, M.L. Roderick, L.T. Li, X.G. Mo, N.E. Zimmermann, and D.R. Schmatz, 2010: Observational evidence from two mountainous regions that near-surface wind speeds are declining more rapidly at higher elevations than lower elevations: 1960-2006. *Geophysical Research Letters*, **37**, L06402, doi:10.1029/2009GL042255.

Medellin-Azuara, J., J.J. Harou, M.A. Olivares, K. Madani, J.R. Lund, R.E. Howitt, S.K. Tanaka, M.W. Jenkins, and T. Zhu, 2008: Adaptability and adaptations of California's water supply system to dry climate warming. *Climatic Change*, **87**, S75-S90.

Mertz, O., K. Halsnæs, J.E. Olesen, and K. Rasmussen, 2009: Adaptation to climate change in developing countries. *Environmental Management*, **43(5)**, 743-752.

Miao, C., J. Ni, A.G.L. Borthwick, and L. Yang, 2011: A preliminary estimate of human and natural contributions to the changes in water discharge and sediment load in the Yellow River. *Global and Planetary Change*, **76(3-4)**, 196-205.

Miles, E.L., M.M. Elsner, J.S. Littell, L.W. Binder, and D.P. Lettenmaier, 2010: Assessing regional impacts and adaptation strategies for climate change: the Washington climate change impacts assessment. *Climatic Change*, **102(1-2)**, 9-27.

Millennium Ecosystem Assessment, 2005: *Ecosystems and Human Well-being: Wetlands and Water: Synthesis.* A Report of the Millennium Ecosystem Assessment, World Resources Institute, Washington DC, USA, 68 pp.

Milly, P.C.D. and K.A. Dunne, 2011: On the hydrologic adjustment of climate-model projections: the potential pitfall of potential evapotranspiration. *Earth Interactions*, **15**, doi: http://dx.doi.org/10.1175/2010EI363.1.

Min, S., X. Zhang, F.W. Zwiers, and G.C. Hegerl, 2011: Human contribution to more-intense precipitation extremes. *Nature*, **470(7334)**, 378-381.

Minville, M., F. Brissette, S. Krau, and R. Leconte, 2009: Adaptation to climate change in the management of a Canadian water-resources system exploited for hydropower. *Water Resources Management*, **23(14)**, 2965-2986.

Miralles, D.G., T.R.H. Holmes, R.A.M. De Jeu, J.H. Gash, A.G.C.A. Meesters, and A.J. Dolman, 2011: Global land-surface evaporation estimated from satellite-based observations. *Hydrology and Earth System Sciences*, **15(2)**, 453-469.

MLIT (Ministry of Land, Infrastructure, Transportation and Tourism in Japan), 2011: Water Resources in Japan. http://www.mlit.go.jp/common/000160806.pdf.

Mogaka, H., S. Gichere, R. Davis, and R Hirji, 2006: *Climate Variability and Water Resources Degradation in Kenya: Improving Water Resources Development and Management*. World Bank Working Paper No. 69, The International Bank for Reconstruction and Development / The World Bank, Washington DC, USA, 108 pp.

Montenegro, A. and R. Ragab, 2010: Hydrological response of a Brazilian semi-arid catchment to different land use and climate change scenarios: a modelling study. *Hydrological Processes*, **24(19)**, 2705-2723.

Mudelsee, M., M. Borngen, G. Tetzlaff, and U. Grunewald, 2003: No upward trends in the occurrence of extreme floods in central Europe. *Nature*, **425(6954)**, 166-169.

Muerth, M.J., B.G. St-Denis, S. Ricard, J.A. Velazquez, J. Schmid, M. Minville, D. Caya, D. Chaumont, R. Ludwig, and R. Turcotte, 2013: On the need for bias correction in regional climate scenarios to assess climate change impacts on river runoff. *Hydrology and Earth System Sciences*, **17(3)**, 1189-1204.

Muller, M., 2007: Adapting to climate change: water management for urban resilience. *Environment and Urbanization*, **19(1)**, 99-113.

Mukhopadhyay, B. and A. Dutta, 2010: A stream water availability model of upper Indus basin based on a topologic model and global climatic datasets. *Water Resources Management*, **24(15)**, 4403-4443.

Munasinghe, M., 2009: Integrated solutions for water, sustainable development and climate change issues: applying the sustainomics framework, In: *On the Water Front* [Lundqvist, J. (ed.)]. Selections from the 2009 World Water Week, Stockholm International Water Institute, Stockholm, Sweden, pp. 46-55.

Murray, S.J., P.N. Foster, and I.C. Prentice, 2012: Future global water resources with respect to climate change and water withdrawals as estimated by a dynamic global vegetation model. *Journal of Hydrology*, **448-449**, 14-29.

Mysiak, J., H.J. Henrikson, C. Sullivan, J. Bromley, and C. Pahl-Wostl (eds.), 2009: *The Adaptive Water Resources Management Handbook*. Earthscan, London, UK, 199 pp.

NACWA, 2009: *Confronting Climate Change: An Early Analysis of Water and Wastewater Adaptation Costs*. National Association of Clean Water Agencies, Washington DC, USA, 104 pp.

Nakaegawa, T., A. Kitoh, M. Hosaka, 2013; Discharge of major global rivers in the late 21st century climate projected with the high horizontal resolution MRI-AGCMs. *Hydrological Processes*, **27(23)**, 3301-3318.

Nassopoulos, H., P. Dumas, and S. Hallegatte, 2012: Adaptation to an uncertain climate change: cost benefit analysis and robust decision making for dam dimensioning. *Climatic Change*, **114(3-4)**, 497-508.

Neupane, R.P. and J.D. White, 2010: *Simulation of Climate Change Impacts on Himalayan Headwater Watershed Snowmelt Hydrology: Discharge*, *Sediment Load*, *and Nutrient Shifts*. Presentation at the 2010 Fall Meeting, American Geophysical Union (AGU), 13-17 December, San Francisco, CA, USA, Abstract No. H43F-1318, abstractsearch.agu.org/meetings/2010/FM/sections/H/sessions/H43F/abstracts/H43F-1318.html.

Ng, G.-H.C., D. McLaughlin, D. Entekhabi, and B.R. Scanlon, 2010: Probabilistic analysis of the effects of climate change on groundwater recharge. *Water Resources Research*, **46**, W07502, doi:10.1029/2009WR007904.

Nicot, J.-P., 2008: Evaluation of large-scale CO_2 storage on fresh-water sections of aquifers: an example from the Texas Gulf Coast basin. *International Journal of Greenhouse Gas Control*, **2(4)**, 582-593.

Noake, K., D. Polson, G. Hegerl, and X. Zhang, 2012: Changes in seasonal land precipitation during the latter twentieth-century. *Geophysical Research Letters*, **39**, L03706, doi:10.1029/2011GL050405.

Nobrega, M.T., W. Collischonn, C.E.M. Tucci, and A.R. Paz, 2011: Uncertainty in climate change impacts on water resources in the Rio Grande basin, Brazil. *Hydrology and Earth System Sciences*, **15(2)**, 585-595.

Nyman, P., G.J. Sheridan, H.G. Smith, and P.N.J. Lane, 2011: Evidence of debris flow occurrence after wildfire in upland catchments of south-east Australia. *Geomorphology*, **125(3)**, 383-401.

OECD, 2010: *Cities and Climate Change*. Organisation for Economic Co-operation and Development (OECD), OECD Publishing, Paris, France, 274 pp., doi:10.1787/9789264091375-en.

OFWAT, 2009: *Climate Change – Good Practice from the 2009 Price Review: Water Today*, *Water Tomorrow*. The Water Services Regulation Authority (OFWAT), Birmingham, UK, 36 pp.

O'Gorman, P.A., 2012: Sensitivity of tropical precipitation extremes to climate change. *Nature Geoscience*, **5(10)**, 697-700.

Okazaki, A., P.J.-F. Yeh, K. Yoshimura, M. Watanabe, M. Kimoto, and T. Oki, 2012: Changes in flood risk under global warming estimated using MIROC5 and the discharge probability index. *Journal of the Meteorological Society of Japan*, **90(4)**, 509-524.

Oki, T. and S. Kanae, 2006: Global hydrological cycles and world water resources. *Science*, **313(5790)**, 1068-1072.

Olhoff, A. and C. Schaer, 2010: *Screening Tools and Guidelines to Support the Mainstreaming of Climate Change Adaptation into Development Assistance – A Stocktaking Report*. United Nations Development Programme (UNDP), New York, NY, USA, 48 pp.

Olsson, J., W. Yang, L.P. Graham, J. Rosberg, and J. Andreasson, 2011: Using an ensemble of climate projections for simulating recent and near-future hydrological change to Lake Vanern in Sweden. *Tellus Series A – Dynamic Meteorology and Oceanography*, **63(1)**, 126-137.

Orlowsky, B. and S.I. Seneviratne, 2013: Elusive drought: uncertainty in observed trends and short- and long-term CMIP5 projections. *Hydrology and Earth System Sciences*, **17(5)**, 1765-1781.

Oude Essink, G. H. P., E.S. van Baaren, and de Louw, P. G. B., 2010: Effects of climate change on coastal groundwater systems: a modeling study in the Netherlands. *Water Resources Research*, **46(10)**, W00F04, doi:10.1029/2009WR008719.

Ozaki, N., T. Fukushima, H. Harasawa, T. Kojiri, K. Kawashima, and M. Ono, 2003: Statistical analyses on the effects of air temperature fluctuations on river water qualities. *Hydrological Processes*, **17(14)**, 2837-2853.

Paerl, H.W. and J. Huisman, 2008: Climate – blooms like it hot. *Science*, **320(5872)**, 57-58.

Paerl, H.W., L.M. Valdes, M.F. Piehler, and C.A. Stow, 2006: Assessing the effects of nutrient management in an estuary experiencing climatic change: the Neuse River Estuary, North Carolina. *Environmental Management*, **37(3)**, 422-436.

Pahl-Wostl, C., 2007: Transitions towards adaptive management of water facing climate and global change. *Water Resources Management*, **21(1)**, 49-62.

Pahl-Wostl, C., P. Kabat, and J. Möltgen (eds.), 2008: *Adaptive and Integrated Water Management: Coping with Complexity and Uncertainty*. Springer Berlin Heidelberg Germany, 440 pp.

Pall, P., T. Aina, D.A. Stone, P.A. Stott, T. Nozawa, A.G.J. Hilberts, D. Lohmann, and M.R. Allen, 2011: Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature*, **470(7334)**, 382-385.

Pednekar, A.M., S.B. Grant, Y. Jeong, Y. Poon, and C. Oancea, 2005: Influence of climate change, tidal mixing, and watershed urbanization on historical water quality in Newport Bay, a saltwater wetland and tidal embayment in southern California. *Environmental Science and Technology*, **39(23)**, 9071-9082.

Pekarova, P., D. Halmova, P. Miklanek, M. Onderka, J. Pekar, and P. Skoda, 2008: Is the water temperature of the Danube River at Bratislava, Slovakia, rising? *Journal of Hydrometeorology*, **9(5)**, 1115-1122.

Petley, D., 2012: Global patterns of loss of life from landslides. *Geology*, **40(10)**, 927-930.

Petrow, T. and B. Merz, 2009: Trends in flood magnitude, frequency and seasonality in Germany in the period 1951-2002. *Journal of Hydrology*, **371(1-4)**, 129-141.

Petrow, T., J. Zimmer, and B. Merz, 2009: Changes in the flood hazard in Germany through changing frequency and persistence of circulation patterns. *Natural Hazards and Earth System Sciences*, **9(4)**, 1409-1423.

Piani, C., J.O. Haerter, and E. Coppola, 2010: Statistical bias correction for daily precipitation in regional climate models over Europe. *Theoretical and Applied Climatology*, **99(1-2)**, 187-192.

Piao, S., P. Friedlingstein, P. Ciais, N. de Noblet-Ducoudre, D. Labat, and S. Zaehle, 2007: Changes in climate and land use have a larger direct impact than rising CO_2 on global river runoff trends. *Proceedings of the National Academy of Sciences of the United States of America*, **104(39)**, 15242-15247.

Piao, S., P. Ciais, Y. Huang, Z. Shen, S. Peng, J. Li, L. Zhou, H. Liu, Y. Ma, Y. Ding, P. Friedlingstein, C. Liu, K. Tan, Y. Yu, T. Zhang, and J. Fang, 2010: The impacts of climate change on water resources and agriculture in China. *Nature*, **467(7311)**, 43-51.

Pinter, N., B.S. Ickes, J.H. Wlosinski, and R.R. van der Ploeg, 2006: Trends in flood stages: contrasting results from the Mississippi and Rhine River systems. *Journal of Hydrology*, **331(3-4)**, 554-566.

Pittock, J. and C.M. Finlayson, 2011: Australia's Murray-Darling basin: freshwater ecosystem conservation options in an era of climate change. *Marine and Freshwater Research*, **62(3)**, 232-243.

Poff, N.L. and J.K.H. Zimmerman, 2010: Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology*, **55(1)**, 194-205.

Portmann, F.T., P. Döll, S. Eisner, and M. Flörke, 2013: Impact of climate change on renewable groundwater resources: assessing the benefits of avoided greenhouse gas emissions using selected CMIP5 climate projections. *Environmental Research Letters*, **8(2)**, 024023, doi:10.1088/1748-9326/8/2/024023.

Prudhomme, C., R.L. Wilby, S. Crooks, A.L. Kay, and N.S. Reynard, 2010: Scenario-neutral approach to climate change impact studies: application to flood risk. *Journal of Hydrology*, **390(3-4)**, 198-209.

Prudhomme, C., S. Parry, J. Hannaford, D.B. Clark, S. Hagemann, and F. Voss, 2011: How well do large-scale models reproduce regional hydrological extremes in Europe? *Journal of Hydrometeorology*, **12(6)**, 1181-1204.

Qian, Y., M.G. Flanner, L.R. Leung, and W. Wang, 2011: Sensitivity studies on the impacts of Tibetan Plateau snowpack pollution on the Asian hydrological cycle and monsoon climate. *Atmospheric Chemistry and Physics*, **11(5)**, 1929-1948.

Qin, B., G. Zhu, G. Gao, Y. Zhang, W. Li, H.W. Paerl, and W.W. Carmichael, 2010: A drinking water crisis in Lake Taihu, China: linkage to climatic variability and lake management. *Environmental Management*, **45(1)**, 105-112.

Quintana Segui, P., A. Ribes, E. Martin, F. Habets, and J. Boe, 2010: Comparison of three downscaling methods in simulating the impact of climate change on the hydrology of Mediterranean basins. *Journal of Hydrology*, **383(1-2)**, 111-124.

Rabassa, J., 2009: Impact of global climate change on glaciers and permafrost of South America, with emphasis on Patagonia, Tierra del Fuego, and the Antarctic Peninsula. *Developments in Earth Surface Processes*, **13**, 415-438.

Rabatel, A., B. Francou, A. Soruco, J. Gomez, B. Caceres, J.L. Ceballos, R. Basantes, M. Vuille, J.-E. Sicart, C. Huggel, M. Scheel, Y. Lejeune, Y. Arnaud, M. Collet, T. Condom, G. Consoli, V. Favier, V. Jomelli, R. Galarraga, P. Ginot, L. Maisincho, J. Mendoza, M. Menegoz, E. Ramirez, P. Ribstein, W. Suarez, M. Villacis, and P. Wagnon, 2013: Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change. *Cryosphere*, **7(1)**, 81-102.

Radić, V., A. Bliss, A.C. Beedlow, R. Hock, E. Miles, and J.G. Cogley, 2013: Regional and global projections of the 21st century glacier mass changes in response to climate scenarios from GCMs. *Climate Dynamics* (in press), doi:10.1007/s00382-013-1719-7.

Raje, D. and P.P. Mujumdar, 2010: Reservoir performance under uncertainty in hydrologic impacts of climate change. *Advances in Water Resources*, **33(3)**, 312-326.

Ramírez, A., S. Hagedoorn, L. Kramers, T. Wildenborg, and C. Hendriks, 2010: Screening CO_2 storage options in The Netherlands. *International Journal of Greenhouse Gas Control*, **4(2)**, 367-380.

Rehana, S. and P.P. Mujumdar, 2012: Climate change induced risk in water quality control problems. *Journal of Hydrology*, **444**, 63-77.

Reiter, P., 2009: *Cities of the Future and Water: Can We Reshape Urban Water and Urban Design to Achieve Long Term Water Security?* Presentation from the 2009 World Water Week, 16-22 August, in Stockholm, Sweden, 68 pp., www.worldwaterweek.org/documents/WWW_PDF/2009/tuesday/T4/future/Reiter_—_Stockholm_2009_COF_Opening.pdf.

Renner, M. and C. Bernhofer, 2012: Applying simple water-energy balance frameworks to predict the climate sensitivity of streamflow over the continental United States. *Hydrology and Earth System Sciences*, **16(8)**, 2531-2546.

Renner, M., R. Seppelt, and C. Bernhofer, 2012: Evaluation of water-energy balance frameworks to predict the sensitivity of streamflow to climate change. *Hydrology and Earth System Sciences*, **16(5)**, 1419-1433.

Renofalt, B.M., R. Jansson, and C. Nilsson, 2010: Effects of hydropower generation and opportunities for environmental flow management in Swedish riverine ecosystems. *Freshwater Biology*, **55(1)**, 49-67.

Rosenzweig, C., G. Casassa, D.J. Karoly, A. Imeson, C. Liu, A. Menzel, S. Rawlins, T.L. Root, B. Seguin, and P. Tryjanowski, 2007: Assessment of observed changes and responses in natural and managed systems. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability*. *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 79-131.

Rost, S., D. Gerten, H. Hoff, W. Lucht, M. Falkenmark, and J. Rockstrom, 2009: Global potential to increase crop production through water management in rainfed agriculture. *Environmental Research Letters*, **4(4)**, 044002, doi:10.1088/1748-9326/4/4/044002.

Rozell, D.J. and S.J. Reaven, 2012: Water pollution risk associated with natural gas extraction from the Marcellus Shale. *Risk Analysis*, **32(8)**, 1382-1393.

Rozemeijer, J.C., H.P. Broers, F.C. van Geer, and M.F.P. Bierkens, 2009: Weather-induced temporal variations in nitrate concentrations in shallow groundwater. *Journal of Hydrology*, **378(1-2)**, 119-127.

Rudberg, P.M., O. Wallgren, and A.G. Swartling, 2012: Beyond generic adaptive capacity: exploring the adaptation space of the water supply and wastewater sector of the Stockholm region, Sweden. *Climatic Change*, **114(3-4)**, 707-721.

Saarinen, T., K.-M. Vuori, E. Alasaarela, and B. Kløve, 2010: Long-term trends and variation of acidity, COD_{Mn} and colour in coastal rivers of western Finland in relation to climate and hydrology. *Science of the Total Environment*, **408(21)**, 5019-5027.

Sadoff, C. and M. Muller, 2009: *Water Management*, *Water Security and Climate Change Adaptation: Early Impacts and Essential Responses*. Global Water Partnership Technical Committee (TEC) Background Paper No. 14, Global Water Partnership, Stockholm, Sweden, 85 pp.

Sahoo, G.B., S.G. Schladow, J.E. Reuter, and R. Coats, 2010: Effects of climate change on thermal properties of lakes and reservoirs, and possible implications. *Stochastic Environmental Research and Risk Assessment*, **25(4)**, 445-456.

Schewe, J., J. Heinke, D. Gerten, I. Haddeland, N.W. Arnell, D.B. Clark, R. Dankers, S. Eisner, B. Fekete, F.J. Colón-González, S.N. Gosling, H. Kim, X. Liu, Y. Masaki, F.T. Portmann, Y. Satoh, T. Stacke, Q. Tang, Y. Wada, D. Wisser, T. Albrecht, K. Frieler, F. Piontek, L. Warszawski, and P. Kabat, 2013: Multi-model assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences of the United States of America* (in press), doi:10.1073/pnas.1222460110.

Scholz, G., J.N. Quinton, and P. Strauss, 2008: Soil erosion from sugar beet in central Europe in response to climate change induced seasonal precipitation variations. *Catena*, **72(1)**, 91-105.

Schwartz, J., R. Levin, and R. Goldstein, 2000: Drinking water turbidity and gastrointestinal illness in the elderly of Philadelphia. *Journal of Epidemiology and Community Health*, **54(1)**, 45-51.

Seah, H., 2008: Energy balances in advanced treatment for new water. In: *Water and Energy Workshop*, *9 September 2008 in Vienna's Austria Centre – Summary* [International Water Association (IWA) (ed.)]. IWA, London, UK, p. 3, www.iwahq.org/ContentSuite/upload/iwa/Document/2008_Vienna_Day2_01.pdf.

Seidu, R., T.A. Stenström, and L. Owe, 2013: A comparative cohort study of the effect of rainfall and temperature on diarrhoeal disease in faecal sludge and non-faecal sludge applying communities, Northern Ghana. *Journal of Water and Climate Change*, **4(2)**, 90-102.

Seneviratne, S.I., D. Lüthi, M. Litschi, and C. Schär, 2006: Land-atmosphere coupling and climate change in Europe. *Nature*, **443(7108)**, 205-209.

Seneviratne, S.I., T. Corti, E.L. Davin, M. Hirschi, E.B. Jaeger, I. Lehner, B. Orlowsky, and A.J. Teuling, 2010: Investigating soil moisture-climate interactions in a changing climate: A review. *Earth-Science Reviews*, **99(3-4)**, 125-161.

Seneviratne, S.I., N. Nicholls, D. Easterling, C.M. Goodess, S. Kanae, J. Kossin, Y. Luo, J. Marengo, K. McInnes, M. Rahimi, M. Reichstein, A. Sorteberg, C. Vera, and X. Zhang, 2012: Changes in climate extremes and their impacts on the natural physical environment. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 109-230.

Senhorst, H.A.J. and J.J.G. Zwolsman, 2005: Climate change and effects on water quality: a first impression. *Water Science and Technology*, **51(5)**, 53-59.

Sheffield, J. and E.F. Wood, 2008: Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. *Climate Dynamics*, **31(1)**, 79-105.

Shiklomanov, A.I., R.B. Lammers, M.A. Rawlins, L.C. Smith, and T.M. Pavelsky, 2007: Temporal and spatial variations in maximum river discharge from a new Russian data set. *Journal of Geophysical Research-Biogeosciences*, **112(G4)**, G04S53, doi:10.1029/2006JG000352.

Short, M.D., W.L. Peirson, G.M. Peters, and R.J. Cox, 2012: Managing adaptation of urban water systems in a changing climate. *Water Resources Management*, **26(7)**, 1953-1981.

Sigel, K., B. Klauer, and C. Pahl-Wostl, 2010: Conceptualising uncertainty in environmental decision-making: the example of the EU Water Framework Directive. *Ecological Economics*, **69(3)**, 502-510.

Skaugen, T., H.B. Stranden, and T. Saloranta, 2012: Trends in snow water equivalent in Norway (1931-2009). *Hydrology Research*, **43(4)**, 489-499.

Smith, H.G., G.J. Sheridan, P.N.J. Lane, P. Nyman, and S. Haydon, 2011: Wildfire effects on water quality in forest catchments: a review with implications for water supply. *Journal of Hydrology*, **396(1-2)**, 170-192.

Smith, L.C., 2000: Trends in Russian Arctic river-ice formation and breakup, 1917 to 1994. *Physical Geography*, **21(1)**, 46-56.

Sprenger, C., G. Lorenzen, I. Hülshoff, G. Grützmacher, M. Ronghang, and A. Pekdeger, 2011: Vulnerability of bank filtration systems to climate change. *Science of the Total Environment*, **409(4)**, 655-663.

Stahl, K., H. Hisdal, J. Hannaford, L.M. Tallaksen, H.A.J. van Lanen, E. Sauquet, S. Demuth, M. Fendekova, and J. Jodar, 2010: Streamflow trends in Europe: evidence from a dataset of near-natural catchments. *Hydrology and Earth System Sciences*, **14(12)**, 2367-2382.

Stahl, K., L.M. Tallaksen, J. Hannaford, and H.A.J. van Lanen, 2012: Filling the white space on maps of European runoff trends: estimates from a multi-model ensemble. *Hydrology and Earth System Sciences*, **16(7)**, 2035-2047.

Stainforth, D.A., M.R. Allen, E.R. Tredger, and L.A. Smith, 2007: Confidence, uncertainty and decision-support relevance in climate predictions. *Philosophical Transactions of the Royal Society A*, **365(1857)**, 2145-2161.

Stakhiv, E.Z., 2011: Pragmatic approaches for water management under climate change uncertainty. *Journal of the American Water Resources Association*, **47(6)**, 1183-1196.

Steele-Dunne, S., P. Lynch, R. McGrath, T. Semmler, S. Wang, J. Hanafin, and P. Nolan, 2008: The impacts of climate change on hydrology in Ireland. *Journal of Hydrology*, **356(1-2)**, 28-45.

Stoll, S., H.J.H. Franssen, R. Barthel, and W. Kinzelbach, 2011: What can we learn from long-term groundwater data to improve climate change impact studies? *Hydrology and Earth System Sciences*, **15(12)**, 3861-3875.

Stott, P.A., N.P. Gillett, G.C. Hegerl, D.J. Karoly, D.A. Stone, X. Zhang, and F. Zwiers, 2010: Detection and attribution of climate change: a regional perspective. *Wiley Interdisciplinary Reviews: Climate Change*, **1(2)**, 192-211.

Stuart-Hill, S.I. and R.E. Schulze, 2010: Does South Africa's water law and policy allow for climate change adaptation? *Climate and Development*, **2(2)**, 128-144.

Sun, F., M.L. Roderick, and G.D. Farquhar, 2012: Changes in the variability of global land precipitation. *Geophysical Research Letters*, **39**, L19402, doi:10.1029/2012GL053369.

Takala, M., J. Pulliainen, S.J. Metsamaki, and J.T. Koskinen, 2009: Detection of snowmelt using spaceborne microwave radiometer data in Eurasia from 1979 to 2007. *IEEE Transactions on Geoscience and Remote Sensing*, **47(9)**, 2996-3007.

Tan, A., J.C. Adam, and D.P. Lettenmaier, 2011: Change in spring snowmelt timing in Eurasian Arctic rivers. *Journal of Geophysical Research: Atmospheres*, **116**, D03101, doi:10.1029/2010JD014337.

Tang, Q. and D.P. Lettenmaier, 2012: 21st century runoff sensitivities of major global river basins. *Geophysical Research Letters*, **39**, L06403, doi:10.1029/2011GL050834.

Taylor, I.H., E. Burke, L. McColl, P.D. Falloon, G.R. Harris, and D. McNeall, 2013: The impact of climate mitigation on projections of future drought. *Hydrology and Earth System Sciences*, **17(6)**, 2339-2358.

Taylor, R., M. Miret-Gaspa, J. Tumwine, L. Mileham, R. Flynn, G. Howard, and R. Kulabako, 2009: Increased risk of diarrhoeal diseases from climate change: evidence from communities supplied by groundwater in Uganda. In: *Groundwater and Climate in Africa* [Taylor, R., C. Tindimugaya, M. Owor, and M. Shamsudduha (eds.)]. Proceedings of the Kampala Conference, 24-28 June 2008, International Association of Hydrological Sciences (IAHS), IAHS Publication No. 334, IAHS Press, Wallingford, UK, pp. 15-19.

Taylor, R.G., B. Scanlon, P. Döll, M. Rodell, R. van Beek, Y. Wada, L. Longuevergne, M. Leblanc, J.S. Famiglietti, M. Edmunds, L. Konikow, T.R. Green, J. Chen, M. Taniguchi, M.F.P. Bierkens, A. MacDonald, Y. Fan, R.M. Maxwell, Y. Yechieli, J.J. Gurdak, D.M. Allen, M. Shamsudduha, K. Hiscock, P.J.-F. Yeh, I. Holman, and H. Treidel, 2013a: Ground water and climate change. *Nature Climate Change*, **3(4)**, 322-329.

Taylor, R.G., M.C. Todd, L. Kongola, L. Maurice, E. Nahozya, H. Sanga, and A.M. MacDonald, 2013b: Evidence of the dependence of groundwater resources on extreme rainfall in East Africa. *Nature Climate Change*, **3(4)**, 374-378.

Tchobanoglous, G., F.L. Burton, and H.D. Stensel (eds.), 2003: *Wastewater Engineering: Treatment and Reuse*. McGraw-Hill Education, Columbus, OH, USA, 1819 pp.

Teng, J., J. Vaze, F.H.S. Chiew, B. Wang, and J. Perraud, 2012: Estimating the relative uncertainties sourced from GCMs and hydrological models in modeling climate change impact on runoff. *Journal of Hydrometeorology*, **13(1)**, 122-139.

Tetzlaff, D., C. Soulsby, and C. Birkel, 2010: Hydrological connectivity and microbiological fluxes in montane catchments: the role of seasonality and climatic variability. *Hydrological Processes*, **24(9)**, 1231-1235.

Teutschbein, C. and J. Seibert, 2012: Bias correction of regional climate model simulations for hydrological climate-change impact studies: review and evaluation of different methods. *Journal of Hydrology*, **456**, 12-29.

Thodsen, H., B. Hasholt, and J.H. Kjærsgaard, 2008: The influence of climate change on suspended sediment transport in Danish rivers. *Hydrological Processes*, **22(6)**, 764-774.

Thöle, D., 2008: Ways to identify possibilities of energy saving at wastewater treatment plants. In: *Water and Energy Workshop*, *9 September 2008 in Vienna's Austria Centre – Summary* [International Water Association (IWA) (ed.)]. IWA, London, UK, pp. 5-6, www.iwahq.org/ContentSuite/upload/iwa/Document/2008_Vienna_Day2_01.pdf.

Thorne, O. and R.A. Fenner, 2011: The impact of climate change on reservoir water quality and water treatment plant operations: a UK case study. *Water and Environment Journal*, **25(1)**, 74-87.

Thorne, R., 2011: Uncertainty in the impacts of projected climate change on the hydrology of a subarctic environment: Liard River basin. *Hydrology and Earth System Sciences*, **15(5)**, 1483-1492.

Tibby, J. and D. Tiller, 2007: Climate-water quality relationships in three western Victorian (Australia) lakes 1984-2000. *Hydrobiologia*, **591(1)**, 219-234.

Towler, E., B. Rajagopalan, E. Gilleland, R.S. Summers, D. Yates, and R.W. Katz, 2010: Modeling hydrologic and water quality extremes in a changing climate: A statistical approach based on extreme value theory. *Water Resources Research*, **46(11)**, W11504, doi:10.1029/2009WR008876.

Trabucco, A., R.J. Zomer, D.A. Bossio, O. van Straaten, and L.V. Verchot, 2008: Climate change mitigation through afforestation/reforestation: a global analysis of hydrologic impacts with four case studies. *Agriculture Ecosystems and Environment*, **126(1-2)**, 81-97.

Trolle, D., D.P. Hamilton, C.A. Pilditch, I.C. Duggan, and E. Jeppesen, 2011: Predicting the effects of climate change on trophic status of three morphologically varying lakes: implications for lake restoration and management. *Environmental Modelling and Software*, **26(4)**, 354-370.

Tumwine, J., A. Kekitiinwa, N. Nabukeera, D. Akiyoshi, M. Buckholt, and S. Tzipori, 2002: Enterocytozoon bieneusi among children with diarrhea attending Mulago Hospital in Uganda. *American Journal of Tropical Medicine and Hygiene*, **67(3)**, 299-303.

Tumwine, J., A. Kekitiinwa, N. Nabukeera, D. Akiyoshi, S. Rich, G. Widmer, X. Feng, and S. Tzipori, 2003: Cryptosporidium parvum in children with diarrhea in Mulago Hospital, Kampala, Uganda. *American Journal of Tropical Medicine and Hygiene*, **68(6)**, 710-715.

UN, 2011: *World Population Prospects: The 2010 Revision*. United Nations, New York, NY, USA, 481 pp.

UNECE, 2009: *Guidance on Water and Adaptation to Climate Change*. United Nations Economic Commission for Europe (UNECE), Geneva, Switzerland, 127 pp.

UNESCO, 2011: *The Impact of Global Change on Water Resources: The Response of UNESCO'S International Hydrology Programme*. United Nations Educational Scientific and Cultural Organization (UNESCO) International Hydrological Programme (IHP), Paris, France, 20 pp.

UNFCCC, 2007: *Investments and Financial Flows to Address Climate Change*. United Nations Framework Convention on Climate Change, Bonn, Germany, 272 pp.

UN-HABITAT, 2008: *State of the World's Cities 2010/2011: Bridging the Urban Divide*. United Nations Human Settlements Programme (UN-HABITAT), Nairobi, Kenya, 224 pp.

Utsumi, N., S. Seto, S. Kanae, E.E. Maeda, and T. Oki, 2011: Does higher surface temperature intensify extreme precipitation? *Geophysical Research Letters*, **38(16)**, L16708, doi:10.1029/2011GL048426.

van Dijk, A.I.J.M. and R.J. Keenan, 2007: Planted forests and water in perspective. *Forest Ecology and Management*, **251(1-2)**, 1-9.

van Huijgevoort, M.H.J., P. Hazenberg, H.A.J. van Lanen, A.J. Teuling, D.B. Clark, S. Folwell, S.N. Gosling, N. Hanasaki, J. Heinke, S. Koirala, T. Stacke, F. Voss, J. Sheffield, and R. Uijlenhoet, 2013: Global multi-model analysis of drought in runoff for the second half of the 20th century. *Journal of Hydrometeorology*, **14(5)**, 1535-1552.

van Pelt, S.C., P. Kabat, H.W. ter Maat, B.J.J.M. van den Hurk, and A.H. Weerts, 2009: Discharge simulations performed with a hydrological model using bias corrected regional climate model input. *Hydrology and Earth System Sciences*, **13(12)**, 2387-2397.

van Roosmalen, L., B.S.B. Christensen, and T.O. Sonnenborg, 2007: Regional differences in climate change impacts on groundwater and stream discharge in Denmark. *Vadose Zone Journal*, **6(3)**, 554-571.

van Vliet, M.T.H. and J.J.G. Zwolsman, 2008: Impact of summer droughts on the water quality of the Meuse river. *Journal of Hydrology*, **353(1-2)**, 1-17.

van Vliet, M.T.H., J.R. Yearsley, F. Ludwig, S. Voegele, D.P. Lettenmaier, and P. Kabat, 2012: Vulnerability of US and European electricity supply to climate change. *Nature Climate Change*, **2(9)**, 676-681.

van Vuuren, D.P., K. Riahi, R. Moss, J. Edmonds, A. Thomson, N. Nakicenovic, T. Kram, F. Berkhout, R. Swart, A. Janetos, S.K. Rose, and N. Arnell, 2012: A proposal for a new scenario framework to support research and assessment in different climate research communities. *Global Environmental Change: Human and Policy Dimensions*, **22(1)**, 21-35.

Vaze, J., D.A. Post, F.H.S. Chiew, J.-M. Perraud, N.R. Viney, and J. Teng, 2010: Climate non-stationarity – validity of calibrated rainfall-runoff models for use in climate change studies. *Journal of Hydrology*, **394(3-4)**, 447-457.

Veijalainen, N., J. Korhonen, B. Vehvilainen, and H. Koivusalo, 2012: Modelling and statistical analysis of catchment water balance and discharge in Finland in 1951-2099 using transient climate scenarios. *Journal of Water and Climate Change*, **3(1)**, 55-78.

Ventela, A., T. Kirkkala, A. Lendasse, M. Tarvainen, H. Helminen, and J. Sarvala, 2011: Climate-related challenges in long-term management of Säkylän Pyhäjärvi (SW Finland). *Hydrobiologia*, **660(1)**, 49-58.

Vidal, J.-P., E. Martin, N. Kitova, J. Najac, and J.-M. Soubeyroux, 2012: Evolution of spatio-temporal drought characteristics: validation, projections and effect of adaptation scenarios. *Hydrology and Earth System Sciences*, **16(8)**, 2935-2955.

Viviroli, D., D.R. Archer, W. Buytaert, H.J. Fowler, G.B. Greenwood, A.F. Hamlet, Y. Huang, G. Koboltschnig, M.I. Litaor, J.I. López-Moreno, S. Lorentz, B. Schädler, H. Schreier, K. Schwaiger, M. Vuille, and R. Woods, 2011: Climate change and mountain water resources: overview and recommendations for research, management and policy. *Hydrology and Earth System Sciences*, **15(2)**, 471-504.

Vörösmarty, C., P. Green, J. Salisbury, and R. Lammers, 2000: Global water resources: vulnerability from climate change and population growth. *Science*, **289(5477)**, 284-288.

Vörösmarty, C.J., P.B. McIntyre, M.O. Gessner, D. Dudgeon, A. Prusevich, P. Green, S. Glidden, S.E. Bunn, C.A. Sullivan, C.R. Liermann, and P.M. Davies, 2010: Global threats to human water security and river biodiversity. *Nature*, **467(7315)**, 555-561.

Wada, Y., D. Wisser, S. Eisner, M. Flörke, D. Gerten, I. Haddeland, N. Hanasaki, Y. Masaki, F.T. Portmann, T. Stacke, Z. Tessler, and J. Schewe, 2013: Multi-model projections and uncertainties of irrigation water demand under climate change. *Geophysical Research Letters*, **40(17)**, 4626-4632.

Walling, D.E., 2009: *The Impact of Global Change on Erosion and Sediment Transport by Rivers: Current Progress and Future Challenges*. The United Nations World Water Assessment Programme (WWAP), Scientific Paper, United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris, France, 26 pp.

Wang, A., D.P. Lettenmaier, and J. Sheffield, 2011: Soil moisture drought in China, 1950-2006. *Journal of Climate*, **24(13)**, 3257-3271.

Wang, D. and X. Cai, 2010: Comparative study of climate and human impacts on seasonal baseflow in urban and agricultural watersheds. *Geophysical Research Letters*, **37**, L06406, doi:10.1029/2009GL041879.

Wang, H., Z. Yang, Y. Saito, J.P. Liu, X. Sun, and Y. Wang, 2007: Stepwise decreases of the Huanghe (Yellow River) sediment load (1950-2005): impacts of climate change and human activities. *Global and Planetary Change*, **57(3-4)**, 331-354.

Wang, J., Sabrina, G. S. A. Rothausen, C. Declan, Z. Lijuan, X. Wei, P.H. Ian, and L. Yumin, 2012: China's water-energy nexus: greenhouse-gas emissions from groundwater use for agriculture. *Environmental Research Letters*, **7(1)**, 014035, doi:10.1088/1748-9326/7/1/014035.

Wang, X., J. Zhang, R. He, E. Amgad, E. Sondoss, and M. Shang, 2011: A strategy to deal with water crisis under climate change for mainstream in the middle reaches of Yellow River. *Mitigation and Adaptation Strategies for Global Change*, **16(5)**, 555-566.

Ward, P.J., K.M. Strzepek, W.P. Pauw, L.M. Brander, G.A. Hughes, and J.C.J.H. Aerts, 2010: Partial costs of global climate change adaptation for the supply of raw industrial and municipal water: a methodology and application. *Environmental Research Letters*, **5(4)**, 044011, doi:10.1088/1748-9326/5/4/044011.

Weatherhead, E.K. and N.J.K. Howden, 2009: The relationship between land use and surface water resources in the UK. *Land use Policy*, **26(Suppl 1)**, S243-S250.

Webb, M.D. and K.W.F. Howard, 2011: Modeling the transient response of saline intrusion to rising sea-levels. *Ground Water*, **49(4)**, 560-569.

Weiland, F.C.S., L.P.H. van Beek, J.C.J. Kwadijk, and M.F.P. Bierkens, 2012a: Global patterns of change in discharge regimes for 2100. *Hydrology and Earth System Sciences*, **16(4)**, 1047-1062.

Weiland, F.C.S., L.P.H. van Beek, J.C.J. Kwadijk, and M.F.P. Bierkens, 2012b: On the suitability of GCM runoff fields for river discharge modeling: a case study using model output from HadGEM2 and ECHAM5. *Journal of Hydrometeorology*, **13(1)**, 140-154.

Werner, A.D., J.D. Ward, L.K. Morgan, C.T. Simmons, N.I. Robinson, and M.D. Teubner, 2012: Vulnerability indicators of sea water intrusion. *Ground Water*, **50(1)**, 48-58.

Whitehead, P.G., R.L. Wilby, R.W. Battarbee, M. Kernan, and A.J. Wade, 2009a: A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences Journal*, **54(1)**, 101-123.

Whitehead, P.G., A.J. Wade, and D. Butterfield, 2009b: Potential impacts of climate change on water quality and ecology in six UK Rivers. *Hydrology Research*, **40(2-3)**, 113-122.

Wilby, R.L., 2010: Evaluating climate model outputs for hydrological applications. *Hydrological Sciences Journal*, **55(7)**, 1090-1093.

Wilby, R.L. and K. Vaughan, 2011: Hallmarks of organisations that are adapting to climate change. *Water and Environment Journal*, **25(2)**, 271-281.

Wilby, R.L., P.G. Whitehead, A.J. Wade, D. Butterfield, R.J. Davis, and G. Watts, 2006: Integrated modelling of climate change impacts on water resources and quality in a lowland catchment: River Kennet, UK. *Journal of Hydrology*, **330(1-2)**, 204-220.

Wilcock, R., S. Elliott, N. Hudson, S. Parkyn, and J. Quinn, 2008: Climate change mitigation for agriculture: water quality benefits and costs. *Water Science and Technology*, **58(11)**, 2093-2099.

Williams, J.G., 2008: Mitigating the effects of high-head dams on the Columbia River, USA: experience from the trenches. *Hydrobiologia*, **609**, 241-251.

Wilson, D., H. Hisdal, and D. Lawrence, 2010: Has streamflow changed in the Nordic countries? – Recent trends and comparisons to hydrological projections. *Journal of Hydrology*, **394(3-4)**, 334-346.

World Bank, 2007: *Guidance Note 7: Evaluating Adaptation via Economic Analysis*. Guidance Notes Series, Mainstreaming Adaptation to Climate Change in Agriculture and Natural Resources Management Projects, Climate Change Team Environment Department, World Bank, Washington DC, USA, 18 pp.

World Bank, 2010: *Economics of Adaptation to Climate Change: Synthesis Report*. World Bank, Washington DC, USA, 101 pp.

Wu, L., Y. Wood, P. Jiang, L. Li, G. Pan, J. Lu, A.C. Chang, and H.A. Enloe, 2008: Carbon sequestration and dynamics of two irrigated agricultural soils in California. *Soil Science Society of America Journal*, **72(3)**, 808-814.

WUCA, 2010: *Decision Support Planning Methods: Incorporating Climate Change Uncertainties into Water Planning*. Water Utility Climate Alliance (WUCA), San Francisco, CA, USA, 102 pp.

WWAP, 2009: *Water in a Changing World*. World Water Development Report 3, World Water Assessment Programme (WWAP), The United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris, France and Earthscan, London, UK, 429 pp.

Xie, Z.C., X. Wang, Q.H. Feng, E.S. Kang, Q.Y. Li and L. Cheng, 2006: Glacial runoff in China: an evaluation and prediction for the future 50 years. *Journal of Glaciology and Geocryology*, **28(4)**, 457-466.

Xu, H., R.G. Taylor, and Y. Xu, 2011: Quantifying uncertainty in the impacts of climate change on river discharge in sub-catchments of the Yangtze and Yellow River basins, China. *Hydrology and Earth System Sciences*, **15(1)**, 333-344.

Yan, X., H. Akiyama, K. Yagi, and H. Akimoto, 2009: Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines. *Global Biogeochemical Cycles*, **23**, GB2002, doi:10.1029/2008GB003299.

Yang, D., S. Kanae, T. Oki, T. Koike, and K. Musiake, 2003: Global potential soil erosion with reference to land use and climate changes. *Hydrological Processes*, **17(14)**, 2913-2928.

Yang, W., J. Andreasson, L.P. Graham, J. Olsson, J. Rosberg, and F. Wetterhall, 2010: Distribution-based scaling to improve usability of regional climate model projections for hydrological climate change impacts studies. *Hydrology Research*, **41(3-4)**, 211-229.

Yasunari, T.J., P. Bonasoni, P. Laj, K. Fujita, E. Vuillermoz, A. Marinoni, P. Cristofanelli, R. Duchi, G. Tartari, and K.-M. Lau, 2010: Estimated impact of black carbon deposition during pre-monsoon season from Nepal Climate Observatory – Pyramid data and snow albedo changes over Himalayan glaciers. *Atmospheric Chemistry and Physics*, **10(14)**, 6603-6615.

Yechieli, Y., E. Shalev, S. Wollman, Y. Kiro, and U. Kafri, 2010: Response of the Mediterranean and Dead Sea coastal aquifers to sea level variations. *Water Resources Research*, **46**, W12550, doi:10.1029/2009WR008708.

Yoo, S.-H., J.-Y. Choi, S.-H. Lee, Y.-G. Oh, and D.K. Yun, 2013: Climate change impacts on water storage requirements of an agricultural reservoir considering changes in land use and rice growing season in Korea. *Agricultural Water Management*, **117**, 43-54.

Yu, X., L. Jiang, L. Li, J. Wang, L. Wang, G. Lei, and J. Pittock, 2009: Freshwater management and climate change adaptation: experiences from the central Yangtze in China. *Climate and Development*, **1(3)**, 241-248.

Zacharias, I. and M. Zamparas, 2010: Mediterranean temporary ponds. A disappearing ecosystem. *Biodiversity and Conservation*, **19(14)**, 3827-3834.

Zhang, X. and X. Cai, 2013: Climate change impacts on global agricultural water deficit. *Geophysical Research Letters*, **40(6)**, 1111-1117.

Zhang, X., F.W. Zwiers, G.C. Hegerl, F.H. Lambert, N.P. Gillett, S. Solomon, P.A. Stott, and T. Nozawa, 2007: Detection of human influence on twentieth-century precipitation trends. *Nature*, **448(7152)**, 461-465.

Zhang, Y.K. and K.E. Schilling, 2006: Increasing streamflow and baseflow in Mississippi River since the 1940s: effect of land use change. *Journal of Hydrology*, **324(1-4)**, 412-422.

Zhang, Z., Q. Zhang, C. Xu, C. Liu, and T. Jiang, 2009: Atmospheric moisture budget and floods in the Yangtze River basin, China. *Theoretical and Applied Climatology*, **95(3-4)**, 331-340.

Ziervogel, G., M. Shale, and M. Du, 2010: Climate change adaptation in a developing country context: the case of urban water supply in Cape Town. *Climate and Development*, **2(2)**, 94-110.

Zimmerman, J.K.H., B.H. Letcher, K.H. Nislow, K.A. Lutz, and F.J. Magilligan, 2010: Determining the effects of dams on subdaily variation in river flows at a whole-basin scale. *River Research and Applications*, **26(10)**, 1246-1260.

Zwolsman, G., D. Vanham, P. Fleming, C. Davis, A. Lovell, D. Nolasco, O. Thorne, R. de Sutter, B. Fülöp, P. Staufer, and Å. Johannessen, 2010: *Climate Change and the Water Industry – Practical Responses and Actions*. Perspectives on Water and Climate Change Adaptation Series, Perpective Document No. 10, Paper prepared by the International Water Association (IWA) Specialist Group on Climate Change (CCSG), on behalf of the IWA, International Water Association, The Hague, Netherlands, 16 pp.

4 Terrestrial and Inland Water Systems

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This chapter should be cited as:

Settele, J., R. Scholes, R. Betts, S. Bunn, P. Leadley, D. Nepstad, J.T. Overpeck, and M.A. Taboada, 2014: Terrestrial and inland water systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 271-359.

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Executive Summary

The planet's biota and ecosystem processes were strongly affected by past climate changes at rates of climate change lower than those projected during the 21st century under high warming scenarios (e.g., Representative Concentration Pathway 8.5 (RCP8.5)) (*high confidence*). Most ecosystems are vulnerable to climate change even at rates of climate change projected under low- to medium-range warming scenarios (e.g., RCP2.6 to RCP6.0). The paleoecological record shows that global climate changes comparable in magnitudes to those projected for the 21st century under all scenarios resulted in large-scale biome shifts and changes in community composition; and that for rates projected under RCP6 and 8.5 were associated with species extinctions in some groups (*high confidence*). {4.2.3}

Climate change is projected to be a powerful stressor on terrestrial and freshwater ecosystems in the second half of the 21st century, especially under high-warming scenarios such as RCP6.0 and RCP8.5 (*high confidence*). Direct human impacts such as land use and land use change, pollution, and water resource development will continue to dominate the threats to most freshwater (*high confidence*) and terrestrial (*medium confidence*) ecosystems globally over the next 3 decades. Changing climate exacerbates other impacts on biodiversity (*high confidence*). Ecosystem changes resulting from climate change may not be fully apparent for several decades, owing to long response times in ecological systems (*medium confidence*). Model-based projections imply that under low to moderate warming scenarios (e.g., RCP2.6 to RCP6.0), direct land cover change will continue to dominate over (and conceal) climate-induced change as a driver of ecosystem change at the global scale; for higher climate change scenarios, some model projections imply climate-driven ecosystem changes sufficiently extensive to equal or exceed direct human impacts at the global scale (*medium confidence*). In high-altitude and high-latitude freshwater and terrestrial ecosystems, climate changes exceeding those projected under RCP2.6 will lead to major changes in species distributions and ecosystem function, especially in the second half of the 21st century (*high confidence*). {4.2.4, 4.3.2.5, 4.3.3, 4.3.3.1, 4.3.3.3, 4.4.1.1}

When terrestrial ecosystems are substantially altered (in terms of plant cover, biomass, phenology, or plant group dominance), either through the effects of climate change or through other mechanisms such as conversion to agriculture or human settlement, the local, regional, and global climates are also affected (*high confidence*). The feedbacks between terrestrial ecosystems and climate include, among other mechanisms, changes in surface albedo, evapotranspiration, and greenhouse gas (GHG) emissions and uptake. The physical effects on the climate can be opposite in direction to the GHG effects, and can materially alter the net outcome of the ecosystem change on the global climate (*high confidence*). The regions where the climate is affected may extend beyond the location of the ecosystem that has changed. {4.2.4.1, 4.3.3.4}

Rising water temperatures, due to global warming, will lead to shifts in freshwater species distributions and worsen water quality problems, especially in those systems experiencing high anthropogenic loading of nutrients (*high confidence*). Climate change-induced changes in precipitation will substantially alter ecologically important attributes of flow regimes in many rivers and wetlands and exacerbate impacts from human water use in developed river basins (*medium confidence*). {4.3.3.3, Box CC-RF}

Many plant and animal species have moved their ranges, altered their abundance, and shifted their seasonal activities in response to observed climate change over recent decades (*high confidence*). They are doing so now in many regions and will continue to do so in response to projected future climate change (*high confidence*). The broad patterns of species and biome shifts toward the poles and higher in altitude in response to a warming climate are well established for periods thousands of years in the past (*very high confidence*). These general patterns of range shifts have also been observed over the last few decades in some well-studied species groups such as insects and birds and can be attributed to observed climatic changes (*high confidence*). Interactions between changing temperature, precipitation, and land use can sometimes result in range shifts that are downhill or away from the poles. Certainty regarding past species movements in response to changing climate, coupled with projections from a variety of models and studies, provides *high confidence* that such species movements will be the norm with continued warming. Under all RCP climate change scenarios for the second half of the 21st century, with *high confidence*: (1) community composition will change as a result of decreases in the abundances of some species and increases in others; and (2) the seasonal activity of many species will change differentially, disrupting life cycles and interactions between species. Composition and seasonal change will both alter ecosystem function. {4.2.1, 4.2.3, 4.3.2, 4.3.2.1, 4.3.2.5, 4.3.3, 4.4.1.1}

Many species will be unable to move fast enough during the 21st century to track suitable climates under mid- and high-range rates of climate change (i.e., RCP4.5, RCP6.0, and RCP8.5 scenarios) (*medium confidence*). The climate velocity (the rate of movement of the climate across the landscape) will exceed the maximum velocity at which many groups of organisms, in many situations, can disperse or migrate, except after mid-century in the RCP2.6 scenario. Populations of species that cannot keep up with their climate niche will find themselves in unfavorable climates, unable to reach areas of potentially suitable climate. Species occupying extensive flat landscapes are particularly vulnerable because they must disperse over longer distances than species in mountainous regions to keep pace with shifting climates. Species with low dispersal capacity will also be especially vulnerable: examples include many plants (especially trees), many amphibians, and some small mammals. For example, the maximum observed and modeled dispersal and establishment rates for mid- and late-successional tree species are insufficient to track climate change except in mountainous areas, even at moderate projected rates of climate change. Barriers to dispersal, such as habitat fragmentation, prior occupation of habitat by competing species, and human-made impediments such as dams on rivers and urbanized areas on land, reduce the ability of species to migrate to more suitable climates (*high confidence*). Intentional and accidental anthropogenic transport can speed dispersal. {4.3.2.5, 4.3.3.3}

Large magnitudes of climate change will reduce the populations, vigor, and viability of species with spatially restricted populations, such as those confined to small and isolated habitats, mountaintops, or mountain streams, even if the species has the biological capacity to move fast enough to track suitable climates (*high confidence*). The adverse effects on restricted populations are modest for low magnitudes of climate change (e.g., RCP2.6) but very severe for the highest magnitudes of projected climate change (e.g., RCP8.5). {4.3.2.5, 4.3.3.4, 4.3.4.1}

The capacity of many species to respond to climate change will be constrained by non-climate factors (*high confidence*), including but not limited to the simultaneous presence of inhospitable land uses, habitat fragmentation and loss, competition with alien species, exposure to new pests and pathogens, nitrogen loading, and tropospheric ozone. {4.2.4.6, 4.3.3.5, Figure 4-4}

The establishment, growth, spread, and survival of populations of invasive alien species have increased (*high confidence*), but the ability to attribute alien species invasion to climate change is low in most cases. Some invasive alien species have traits that favor their survival and reproduction under changing climates. Future movement of species into areas where they were not present historically will continue to be driven mainly by increased dispersal opportunities associated with human activities and by increased disturbances from natural and anthropogenic events, in some cases facilitated and promoted by climate change. {4.2.4.6, Figure 4-4}

A large fraction of terrestrial and freshwater species face increased extinction risk under projected climate change during and beyond the 21st century, especially as climate change interacts with other pressures, such as habitat modification, overexploitation, pollution, and invasive species (*high confidence*). The extinction risk is increased under all RCP scenarios, and the risk increases with both the magnitude and rate of climate change. While there is *medium confidence* that recent warming contributed to the extinction of some species of Central American amphibians, there is generally *very low confidence* that observed species extinctions can be attributed to recent climate change. Models project that the risk of species extinctions will increase in the future owing to climate change, but there is *low agreement* concerning the fraction of species at increased risk, the regional and taxonomic focus for such extinctions and the time frame over which extinctions could occur. Modeling studies and syntheses since the AR4 broadly confirm that a large proportion of species are projected to be at increased risk of extinction at all but the lowest levels of climate warming (RCP2.6). Some aspects leading to uncertainty in the quantitative projections of extinction risks were not taken into account in previous models; as more realistic details are included, it has been shown that the extinction risks may be either under- or overestimated when based on simpler models. {4.3.2.5}

Terrestrial and freshwater ecosystems have sequestered about a quarter of the carbon dioxide (CO_2) emitted to the atmosphere by human activities in the past 3 decades (*high confidence*). The net fluxes out of the atmosphere and into plant biomass and soils show large year-to-year variability; as a result there is *low confidence* in the ability to determine whether the net rate at which carbon has been taken up by terrestrial ecosystems at the global scale has changed between the decades 1991–2000 and 2001–2010. There is *high confidence* that the factors causing the current increase in land carbon include the positive effects of rising CO_2 on plant productivity, a warming climate, nitrogen deposition, and recovery from past disturbances, but *low confidence* regarding the relative contribution by each of these and other factors. {4.2.4.1, 4.2.4.2, 4.2.4.4, 4.3.2.2, 4.3.2.3, WGI AR5 6.3.1, 6.3.2.6}

The natural carbon sink provided by terrestrial ecosystems is partially offset at the decadal time scale by carbon released through the conversion of natural ecosystems (principally forests) to farm and grazing land and through ecosystem degradation (*high confidence*). Carbon stored in the terrestrial biosphere is vulnerable to loss back to the atmosphere as a result of the direct and indirect effects of climate change, deforestation, and degradation (*high confidence*). The net transfer of CO_2 from the atmosphere to the land is projected to weaken during the 21st century (*medium confidence*). The direct effects of climate change on stored terrestrial carbon include high temperatures, drought, and windstorms; indirect effects include increased risk of fires and pest and disease outbreaks. Experiments and modeling studies provide *medium confidence* that increases in CO_2 up to about 600 ppm will continue to enhance photosynthesis and plant water use efficiency, but at a diminishing rate; and *high confidence* that low availability of nutrients, particularly nitrogen, will limit the response of many natural ecosystems to rising CO_2. There is *medium confidence* that other factors associated with global change, including high temperatures, rising ozone concentrations, and in some places drought, decrease plant productivity by amounts comparable in magnitude to the enhancement by rising CO_2. There are few field-scale experiments on ecosystems at the highest CO_2 concentrations projected by RCP8.5 for late in the century, and none of these include the effects of other potential confounding factors. {4.2.4, 4.2.4.1, 4.2.4.2, 4.2.4.3, 4.2.4.4, 4.3.2.2, 4.3.3.1, Box 4-3, Box CC-VW, WGI AR5 6.4.3.3}

Increases in the frequency or intensity of ecosystem disturbances such as droughts, wind storms, fires, and pest outbreaks have been detected in many parts of the world and in some cases are attributed to climate change (*medium confidence*). Changes in the ecosystem disturbance regime beyond the range of natural variability will alter the structure, composition, and functioning of ecosystems (*high confidence*). Ecological theory and experimentation predict that ecological change resulting from altered disturbance regimes will be manifested as relatively abrupt and spatially patchy transitions in ecosystem structure, composition, and function, rather than gradual and spatially uniform shifts in location or abundance of species (*medium confidence*). {4.2.4.6, 4.3.3, 4.3.2.5, Box 4-3, Box 4-4, Figure 4-10}

Increased tree death has been observed in many places worldwide, and in some regions has been attributed to climate change (*high confidence*). In some places it is sufficiently intense and widespread as to result in forest dieback (*low confidence*). Forest dieback is a major environmental risk, with potentially large impacts on climate, biodiversity, wood production, water quality, amenity, and economic activity. In detailed regional studies in western and boreal North America, the tree mortality observed over the past few decades has been attributed to the effects of high temperatures and drought, or to changes in the distribution and abundance of insect pests and pathogens related, in part, to warming (*high confidence*). Tree mortality and associated forest dieback will become apparent in many regions sooner than previously anticipated (*medium confidence*). Earlier projections of increased tree growth and enhanced forest carbon sequestration due to increased growing season duration, rising CO_2 concentration, and atmospheric nitrogen deposition must be balanced by observations and projections of increasing tree mortality and forest loss due to fires and pest attacks. The consequences for the provision of timber and other wood products are projected to be highly variable between regions and products, depending on the balance of the positive versus negative effects of global change. {4.3.2, 4.3.3.1, 4.3.3.4, 4.3.3.5, 4.3.4, 4.3.4.2, Box 4-2, Box 4-3}

There is a high risk that the large magnitudes and high rates of climate change associated with low-mitigation climate scenarios (RCP4.5 and higher) will result within this century in abrupt and irreversible regional-scale change in the composition, structure, and function of terrestrial and freshwater ecosystems, for example in the Amazon (*low confidence*) and Arctic (*medium confidence*), leading to substantial additional climate change. There are plausible mechanisms, supported by experimental evidence, observations, and model results, for the existence of ecosystem tipping points in both boreal-tundra Arctic systems and the rainforests of the Amazon basin. Continued climate change will transform the species composition, land cover, drainage, and permafrost extent of the boreal-tundra system, leading to decreased albedo and the release of GHGs (*medium confidence*). Adaptation measures will be unable to prevent substantial change in the boreal-Arctic system (*high confidence*). Climate change alone is not projected to lead to abrupt widespread loss of forest cover in the Amazon during this century a (*medium confidence*), but a projected increase in severe drought episodes, together with land use change and forest fire, would cause much of the Amazon forest to transform to less dense, drought- and fire-adapted ecosystems, and in doing so put a large stock of biodiversity at elevated risk, while decreasing net carbon uptake from the atmosphere (*low confidence*). Large reductions in deforestation, as well as wider application of effective wildfire management, lower the risk of abrupt change in the Amazon, as well as the impacts of that change (*medium confidence*). {4.2.4.1, 4.3.3.1.1, 4.3.3.1.3, 4.3.3.4, Figure 4-8, Box 4-3, Box 4-4}

Management actions can reduce, but not eliminate, the risk of impacts to terrestrial and freshwater ecosystems due to climate change, as well as increase the inherent capacity of ecosystems and their species to adapt to a changing climate (*high confidence*). The capacity for natural adaptation by ecosystems and their constituent organisms is substantial, but for many ecosystems and species it will be insufficient to cope with projected rates and magnitudes of climate change in the 21st century without substantial loss of species and ecosystem services, under medium-range warming (e.g., RCP6.0) or high-range warming scenarios (e.g., RCP8.5) (*medium confidence*). The capacity for ecosystems to adapt to climate change can be increased by reducing the other stresses operating on them; reducing the rate and magnitude of climate change; reducing habitat fragmentation and increasing connectivity; maintaining a large pool of genetic diversity and functional evolutionary processes; assisted translocation of slow moving organisms or those whose migration is impeded, along with the species on which they depend; and manipulation of disturbance regimes to keep them within the ranges necessary for species persistence and sustained ecosystem functioning. {4.4, 4.4.1, 4.4.2}

Adaptation responses to climate change in the urban and agricultural sectors can have unintended negative outcomes for terrestrial and freshwater ecosystems (*medium confidence*). For example, adaptation responses to counter increased variability of water supply, such as building more and larger impoundments and increased water extraction, will in many cases worsen the direct effects of climate change in freshwater ecosystems. {4.3.3.3, 4.3.4.6}

Widespread transformation of terrestrial ecosystems in order to mitigate climate change, such as carbon sequestration through planting fast-growing tree species into ecosystems where they did not previously occur, or the conversion of previously uncultivated or non-degraded land to bioenergy plantations, will lead to negative impacts on ecosystems and biodiversity (*high confidence*). For example, the land use scenario accompanying the mitigation scenario RCP2.6 features a large expansion of biofuel production, displacing natural forest cover. {4.2.4.1, 4.4.4}

4.1. Past Assessments

The topics assessed in this chapter were last assessed by the IPCC in 2007, principally in WGII AR4 Chapters 3 (Kundzewicz et al., 2007) and 4 (Fischlin et al., 2007), but also in WGII AR4 Sections 1.3.4 and 1.3.5 (Rosenzweig et al., 2007). The WGII AR4 SPM stated "Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases," though they noted that documentation of observed changes in tropical regions and the Southern Hemisphere was sparse (Rosenzweig et al., 2007). Fischlin et al. (2007) found that 20 to 30% of the plant and animal species that had been assessed to that time were considered to be at increased risk of extinction if the global average temperature increase exceeds 2°C to 3°C above the preindustrial level with *medium confidence*, and that substantial changes in structure and functioning of terrestrial, marine, and other aquatic ecosystems are *very likely* under that degree of warming and associated atmospheric CO_2 concentration. No time scale was associated with these findings. The carbon stocks in terrestrial ecosystems were considered to be at high risk from climate change and land use change. The report warned that the capacity of ecosystems to adapt naturally to the combined effect of climate change and other stressors is likely to be exceeded if greenhouse gas (GHG) emission continued at or above the then-current rate.

4.2. A Dynamic and Inclusive View of Ecosystems

There are three aspects of the contemporary scientific view of ecosystems that are important to know for policy purposes. First, ecosystems usually have imprecise and variable boundaries. They span a wide range of spatial scales, nested within one another, from the whole biosphere, down through its major ecosystem types (biomes), to local and possibly short-lived associations of organisms. Second, the human influence on ecosystems is globally pervasive. Humans are regarded as an integral, rather than separate, part of social-ecological systems (Gunderson and Holling, 2001; Berkes et al., 2003). Ecosystems are connected across boundaries through the movement of energy, materials, and organisms, and subsidies between terrestrial and freshwater systems are known to be particularly important (Polis et al., 1997; Loreau et al., 2003). As a consequence, human activities in terrestrial systems can significantly impact freshwater ecosystems and their biota (Allan, 2004). The dynamics of socio-ecological systems are governed not only by biophysical processes such as energy flows, material cycles, competition, and predation, but also by social processes such as economics, politics, culture, and individual preferences (Walker and Salt, 2006). Third, ecologists do not view ecosystems as necessarily inherently static and at equilibrium in the absence of a human disturbance (Hastings, 2004). Ecosystems vary over time and space in the relative magnitude of their components and fluxes, even under a constant environment, owing to internal dynamics (Scheffer, 2009). Furthermore, attempts to restrict this intrinsic variation—or that resulting from externally generated disturbances—are frequently futile, and may damage the capacity of the ecosystem to adapt to a changing environment (Folke et al., 2004). This contrasts with the popular view that ecosystems exhibit a "balance of Nature" and benefit from being completely protected from disturbance.

4.2.1. Ecosystems, Adaptation, Thresholds, and Tipping Points

The term "adaptation" has different meanings in climate policy, ecology, and evolutionary biology. In climate policy (see Glossary) it implies human actions intended to reduce negative outcomes. In ecology, ecosystems are said to be adaptive because their composition or function can change in response to a changing environment, without necessarily involving deliberate human actions (see Section 4.4.1). In evolutionary biology, adaptation means a change in the genetic properties of a population of individuals as a result of natural selection (Section 4.4.1.2), a possibility seen since the Fourth Assessment Report as increasingly relevant to climate change.

The notion of thresholds has become a prominent ecological and political concern (Knapp, A.K. et al., 2008; Lenton et al., 2008; Leadley et al., 2010). To avoid policy confusion, three types of threshold need to be distinguished. The first reflects a human preference that the ecosystem stays within certain bounds, such as above a certain forest cover. These can be, by definition, negotiated. The second type reflects fundamental biological or physical properties, for instance the temperature at which frozen soils thaw (see Box 4-4) or the physiological tolerance limits of species. The third type is caused by system dynamics: the point at which the net effect of all the positive and negative feedback loops regulating the system is sufficiently large and positive that a small transgression becomes sufficiently amplified to lead to a change in ecosystem state called a regime shift (Lenton et al., 2008). The new state exhibits different dynamics, mean composition, sensitivity to environmental drivers, and flows of ecosystem services relative to the prior state. This type of threshold is called a "tipping point" (defined in the Glossary as a level of change in system properties beyond which a system reorganizes, often abruptly, and persists in its new state even if the drivers of the change are abated) and is important in the context of climate change because its onset may be abrupt, hard to predict precisely, and effectively irreversible (Scheffer et al., 2009; Leadley et al., 2010; Barnosky et al., 2012; Brook et al., 2013; Hughes et al., 2013). Many examples of tipping points have now been identified (Scheffer, 2009). Regional-scale ecosystem tipping points have not occurred in the recent past, but there is good evidence for tipping points in the distant past (Section 4.2.3) and there is concern that they could occur in the near future (see Boxes 4-3 and 4-4).

The early detection and prediction of ecosystem thresholds, particularly tipping points, is an area of active research. There are indications (Scheffer, 2009) that an increase in ecosystem variability signals the impending approach of a threshold. In practice, such signals may not be detectable against background noise and uncertainty until the threshold is crossed (Biggs et al., 2009). The dynamics of ecosystems are complex and our present level of knowledge is inadequate to predict all ecosystem outcomes with confidence, even if the future climate were precisely known.

Field observations over the past century in numerous locations in boreal, temperate, and tropical ecosystems have detected biome shifts, the replacement at a location of one suite of species by another (*high confidence*). The effect is usually of biomes moving upward in elevation and to higher latitudes (Gonzalez et al., 2010; see Figure 4-1). These shifts

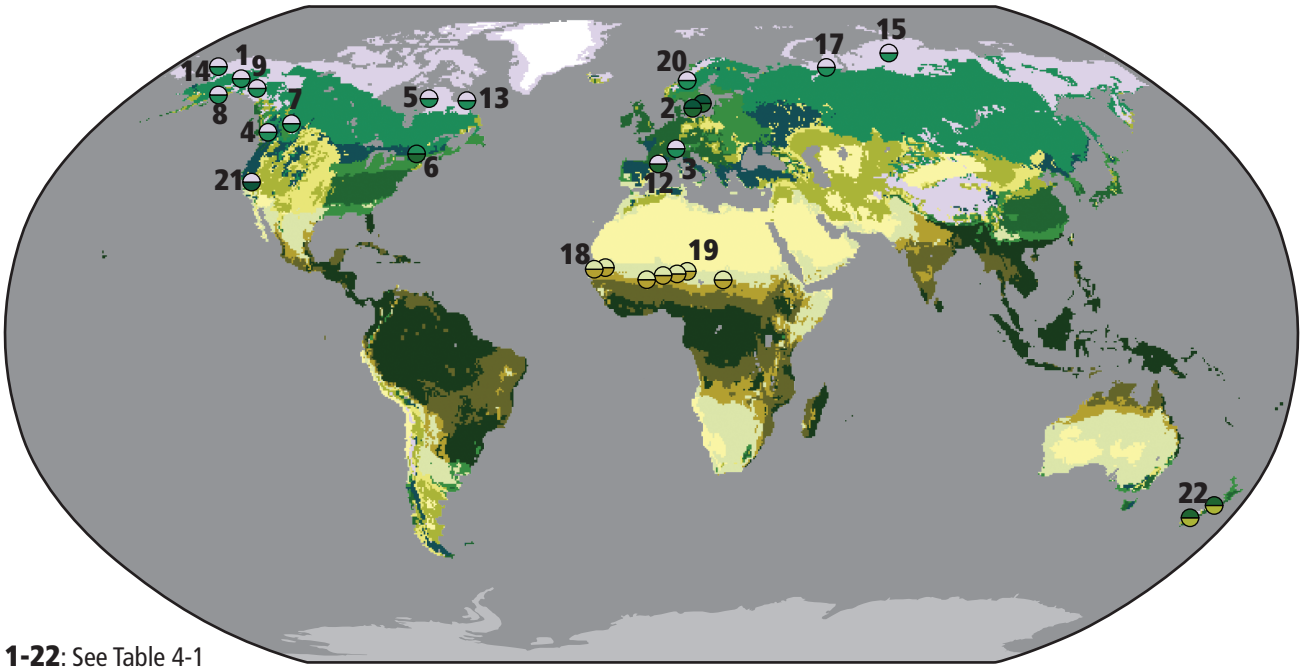


Figure 4-1 | Locations of observed biome shifts during the 20th century, listed in Table 4-1, derived from Gonzalez et al. (2010). The color of each semicircle indicates the retracting biome (top for North America, Europe, Asia; bottom for Africa and New Zealand) and the expanding biome (bottom for North America, Europe, Asia; top for Africa and New Zealand), according to published field observations. Biomes, from poles to equator: ice (IC), tundra and alpine (UA), boreal conifer forest (BC), temperate conifer forest (TC), temperate broadleaf forest (TB), temperate mixed forest (TM), temperate shrubland (TS), temperate grassland (TG), desert (DE), tropical grassland (RG), tropical woodland (RW), tropical deciduous broadleaf forest (RD), tropical evergreen broadleaf forest (RE). The background is the potential biome according to the MC1 dynamic global vegetation model under the 1961–1990 climate. No shift was observed on locations 10, 11, 16, and 23 (see Table 4-1).

have often been attributed to anthropogenic climate change, as biome distribution is known to broadly reflect climate zones, and the shifts have been observed in areas without major human disturbance (*medium confidence*; see Table 4-1). Projections of future vegetation distribution under climate change indicate that many biomes could shift substantially, including in areas where ecosystems are largely undisturbed by direct human land use (Figure 4-2). The extent of the shift increases with increasing global mean warming, without a sudden threshold (Scholze et al., 2006; Pereira et al., 2010; Rehfeldt et al., 2012).

4.2.2. Methods and Models Used

Analysis of the current and past impacts of climate change on terrestrial and freshwater ecosystems and their projection into the future relies on three general approaches: inference from analogous situations in the past or elsewhere in the present; manipulative experimentation, deliberately altering one of a few factors at a time; and models with a mechanistic or statistical basis. Studies of the relatively distant past are discussed in depth in Section 4.2.3. Inferences from present spatial patterns in relation to climate is at the core of climate envelope niche modeling, a well-established but limited statistical technique for making projections of the future distribution under equilibrium conditions (Elith and Leathwick, 2009). Representing the rate of change during the non-equilibrium conditions that will prevail over the next century requires a more mechanistic approach, of which there are some examples (e.g., Keith et al., 2008; Kearney and Porter, 2009). Changes in ecosystem function are usually determined by experimentation (see examples in Section 4.3.3) and are modeled using mechanistic models, in many cases with relatively high uncertainty (Seppelt et al., 2011).

4.2.3. Paleoecological Evidence

Paleoclimatic observations and modeling indicate that the Earth's climate has always changed on a wide range of time scales. In many cases, particularly over the last million years, it has changed in ways that are well understood in terms of both patterns and causes (Jansen et al., 2007; see WGI AR5 Chapter 5). Paleoecological records demonstrate with *high confidence* that the planet's biota (both terrestrial and aquatic),

Table 4-1 | Biome shifts of the 20th century from published field research that examined trends over periods >30 years for biomes in areas where climate (rather than land use change or other factors) predominantly influenced vegetation, derived from a systematic analysis of published studies (Gonzalez et al., 2010). Pre-AR4 publications are included to provide a comprehensive review. Shift type: elevational (E), latitudinal (L), examined but not detected (N). The biome abbreviations match those in Figure 4-1. Rate of change in temperature (Temp.) and fractional rate of change in precipitation (Precip.) are derived from linear least squares regression of 1901–2002 data (Mitchell and Jones, 2005; Gonzalez et al., 2010). The table provides general regional climate trends at 50 km spatial resolution because the references do not give uniform site-specific climate data to compare across locations. The regional trends are consistent with local trends reported in each reference. *Rate significant at $P \leq 0.05$.

Location	Reference	Plots	Time period	Shift type	Retracting biome	Expanding biome	Temp. change (°C century^{-1})	Precip. change (% century^{-1})
1. Alaska Range, Alaska, USA	Lloyd and Fastie (2003)	18	1800–2000	L	UA	BC	1.1*	3
2. Baltic Coast, Sweden	Walther et al. (2005)	7	1944–2003	L	TC	TB	0.6*	8
3. Becca di Viou, Italy	Leonelli et al. (2011)	1	1700–2008	E	UA	BC	0.9*	–6
4. Garibaldi, British Columbia, Canada	Brink (1959)	1	1860–1959	E	UA	BC	0.7*	16*
5. Goulet Sector, Québec, Canada	Payette and Filion (1985)	2	1880–1980	E	UA	BC	1.4*	19*
6. Green Mountains, Vermont, USA	Beckage et al. (2008)	33	1962–2005	E	BC	TB	1.6*	6
7. Jasper, Alberta, Canada	Luckman and Kavanagh (2000)	1	1700–1994	E	UA	BC	0.6	21*
8. Kenai Mountains, Alaska, USA	Dial et al. (2007)	3	1951–1996	E	UA	BC	0.7	6
9. Kluane Range, Yukon, Canada	Danby and Hik (2007)	2	1800–2000	E	UA	BC	0.7	5
10. Low Peninsula, Québec, Canada	Payette and Filion (1985)	1	1750–1980	N	—	—	1.4*	19*
11. Mackenzie Mountains, Northwest Territories, Canada	Szeicz and Macdonald (1995)	13	1700–1990	N	—	—	1.4*	3
12. Montseny Mountains, Catalonia, Spain	Peñuelas and Boada (2003)	50	1945–2001	E	UA	TB	1.2*	–3
13. Napaktok Bay, Labrador, Canada	Payette (2007)	2	1750–2000	L	UA	BC	1.1*	5
14. Noatak, Alaska, USA	Suarez et al. (1999)	18	1700–1990	L	UA	BC	0.6	19*
15. Putorana Mountains, Russian Federation	Kirdyanov et al. (2012)	10	1500–2000	E	UA	BC	0.3	10
16. Rahu Saddle, New Zealand	Cullen et al. (2001)	7	1700–2000	N	—	—	0.6*	3
17. Rai-Iz, Urals, Russian Federation	Devi et al. (2008)	144	1700–2002	E	UA	BC	0.3	35*
18. Sahel, Sudan, Guinea zones; Senegal	Gonzalez (2001)	135	1945–1993	L	RW	RG	0.4*	–48*
19. Sahel, Burkina Faso, Chad, Mali, Mauritania, Niger	Gonzalez et al. (2012)	14	1960–2000	L	RW	RG	–0.01* to 0.8*	–31* to 9
20. Scandes, Sweden	Kullman and Öberg (2009)	123	1915–2007	E	UA	BC	0.8*	25*
21. Sierra Nevada, California, USA	Millar et al. (2004)	10	1880–2002	E	UA	TC	–0.1	21*
22. South Island, New Zealand	Wardle and Coleman (1992)	22	1980–1990	E	TS	TB	0.6*	3
23. Yambarran, Northern Territory, Australia	Sharp and Bowman (2004)	33	1948–2000	N	—	—	–0.06	35*

carbon cycle, and associated feedbacks and services have responded to this climatic change, particularly when the climatic change was as large as that projected during the 21st century under mid- to high-end radiative forcing pathways (e.g., MacDonald et al., 2008; Claussen, 2009; Arneth et al., 2010; Dawson et al., 2011; Willis and MacDonald, 2011). Excellent examples of past large climate change events that drove large ecological change, as well as recovery periods in excess of a million years, include the events that led to the Earth's five mass extinctions in the distant past (i.e., during the Ordovician, about 443 Ma, the Devonian, about 359 Ma, the Permian, about 251 Ma, the Triassic, about 200 Ma, and the Cretaceous, about 65 Ma; Barnosky et al., 2011). Major ecological change was also driven by climate change during the Paleocene-Eocene Thermal Maximum (PETM, 56 Ma; Wing et al., 2005; Jaramillo et al., 2010; Wing and Currano, 2013), the early Eocene Climatic Optimum (EECO, 53 to 50 Ma; Woodburne et al., 2009), the Pliocene (5.3 to 2.6 Ma; Haywood and Valdes, 2006; Haywood et al., 2011), and the Last Glacial Maximum (LGM) to Holocene transition between 21 and 6 ka (MacDonald et al., 2008; Clark et al., 2009; Gill et al., 2009; Williams, J.W. et al., 2010; Prentice et al., 2011; Daniau et al., 2012). The paleoecological record thus provides *high confidence* that large global climate change, comparable in magnitude to that projected for the 21st century, can result in large ecological changes, including large-scale biome shifts, reshuffling of communities, and species extinctions.

Rapid, regional warming before and after the Younger Dryas cooling event (11.7 to 12.9 ka) provides a relatively recent analogy for climate change at a rate approaching, for many regions, that projected for the 21st century for all Representative Concentration Pathways (RCPs; Alley et al., 2003; Steffensen et al., 2008). Ecosystems and species responded rapidly during the Younger Dryas by shifting distributions and abundances, and there were some notable large animal extinctions, probably exacerbated by human activities (Gill et al., 2009; Dawson et al., 2011). In some regions, species became locally or regionally extinct (extirpated), but there is no evidence for climate-driven global-scale extinctions during this period (Botkin et al., 2007; Willis, K.J. et al., 2010). However, the Younger Dryas climate changes differ from those projected for the future because they were regional rather than global; may have only regionally exceeded rates of warming projected for the future; and started from a baseline substantially colder than present (Alley et al., 2003). The mid-Holocene, about 6 ka, provides a very recent example of the effects of modest climate change. Regional mean warming during this period (mean annual temperature about 0.5°C to 1.0°C above

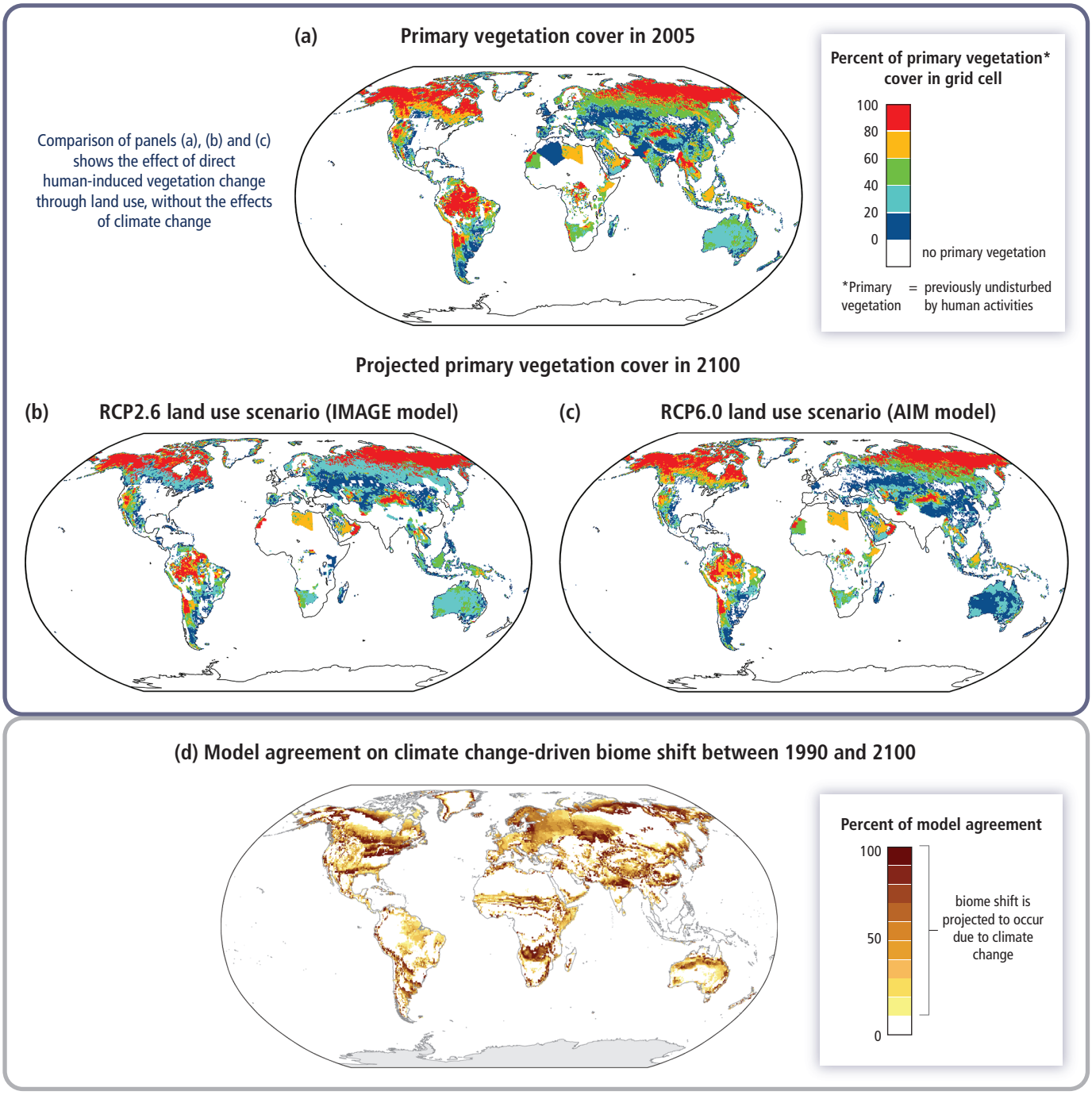


Figure 4-2 | Projections of climate change-driven biome shifts in the context of direct human land use. (a) Fraction of land covered by primary vegetation in 2005 (Hurtt et al., 2011); (b) Fraction of land covered by primary vegetation in 2100 under the RCP2.6 land use scenario, with no effect of climate change (Hurtt et al., 2011); (c) Fraction of land covered by primary vegetation in 2100 under the RCP6.0 land use scenario, with no effect of climate change (Hurtt et al., 2011). (d) Fraction of simulations showing climate change-driven biome shift for any level of global warming between 1990 and 2100, with no direct anthropogenic land use change, using the MC1 vegetation model under 9 CMIP3 climate projections (3 GCMs, each forced by the SRES A2, A1B, and B1 scenarios; Gonzalez et al., 2010); Comparison of colored areas in (d) with those in (a) shows where climate-driven biome shifts would occur in current areas of primary vegetation. Comparison of (b) and (c) with (a) illustrates two scenarios of how primary vegetation could change due to direct human land use, irrespective of the effects of climate change. (b) shows the land use scenario associated with RCP2.6, in which global climate change is projected to be smaller than that driving the biome shifts in (d) as a result of mitigation measures, some of which involved land use. (c) shows the land use scenario associated with RCP6.0, in which global climate change is projected to be larger than RCP2.6 so biome shifts similar to those in (d) may occur alongside the projected land use changes in (c). For example, climate change-driven biome shift is projected in many Arctic land areas (d) which are unaffected by direct human land use at the present day (a) and in the RCP2.6 and 6.0 land use scenarios (b, c), indicating that climate change is the dominant influence on Arctic land ecosystems in these scenarios. In contrast, in Borneo, none of the GCMs analysed by Gonzalez et al. (2010) project climate change-driven biome shift (d), and instead a reduction in primary vegetation cover occurs in the mitigation scenario RCP2.6 as a consequence of direct human land use (b). A smaller reduction occurs in RCP6.0. Land use is therefore projected to be the dominant driver of change in Borneo in these scenarios. In the boreal forest regions of North America, Europe, and north-west Asia, climate change-driven biome shift (d) is projected in regions already subject to some influence of present-day human land use (a), and increased land use leading to further reductions in primary vegetation occur in both RCP2.6 (b) and RCP6.0 (c). Hence in these boreal forest regions, both climate change and land use are projected to be drivers of ecosystem change in these scenarios. Further details of the RCP land use/cover scenarios are given in Box 4-1, Figure 4-3, and Table 4-2.

preindustrial in some continental-scale regions; see WGI AR5 Section 5.5.1) was the same order of magnitude as the warming the Earth has experienced over the 20th century. Ecological effects were small compared to periods with larger climate excursions, but even this small warming was characterized by frequent fires in drier parts of the Amazon (Mayle and Power, 2008), development of lush vegetation and lakes in a wetter Sahara (Watrin et al., 2009), temperate deciduous forests in Europe expanding further north and up to higher elevations (Prentice et al., 1996), and large-scale migration of Boreal Forest into a warmer tundra (Jackson and Overpeck, 2000). Past climate change, even more modest than mid-range projected future change, also clearly impacted inland water systems (e.g., Smol and Douglas, 2007a; Battarbee et al., 2009; Beilman et al., 2009). However, there are no exact analogs for future climate change: none of the well-studied past periods of large climate change involved simultaneously the rates, magnitude, and spatial scale of climate and atmospheric carbon dioxide (CO_2) change projected for the 21st century and beyond (Jansen et al., 2007; Schulte et al., 2010; Wing and Currano, 2013; see WGI AR5 Chapter 5). Direct analogy with the paleoecological record is also unwarranted because future climate change will interact with other global changes such as land use change, invasive species, pollution, and overexploitation of natural resources (Pereira et al., 2010). There is *high confidence* that these interactions will be important: the paleoecological record provides *medium confidence* (*medium evidence*, *high agreement*) that exploitation by humans helped drive many large mammal species to extinction during periods of climate change in the past (Lorenzen et al., 2011).

It has been demonstrated that state-of-the-art vegetation models are able to simulate much of the biome-level equilibrium response of terrestrial vegetation to large paleoclimate change (Prentice et al., 1996, 2011; Salzmann et al., 2008). The same types of models predict large changes in species ranges, ecosystem function, and carbon storage when forced by 21st century climate change, although the future situation is complicated by land use and other factors absent in the paleoenvironmental case (Sitch et al., 2008; Cheaib et al., 2012; see WGI AR5 Section 6.4). Thus, the paleoecological record and models that have been tested against it provide a coherent message that biomes will alter their functioning and composition in response to changing and often novel future climates: they will move as species mixtures change (Section 4.3.2.5 has more specific information on projected migration rates), novel plant communities will emerge, and significant carbon stock changes will take place (Williams and Jackson, 2007; MacDonald, 2010; Prentice et al., 2011; Willis and MacDonald, 2011). The paleoecological record and models provide *high confidence* that it will be difficult or impossible to maintain many ecological systems in their current states if global warming exceeds 2°C to 3°C, raising questions about the long-term viability of some current protected areas and conservation schemes, particularly where the objective is to maintain present-day species mixtures (Jackson and Hobbs, 2009; Hickler et al., 2012).

Much of the complex, time-dependent change at regional scales has not yet been simulated by models. The paleoecological record indicates that vegetation in many parts of the world has the potential to respond within years to a few decades to climate change (e.g., Mueller, A.D. et al., 2009; Watrin et al., 2009; Williams et al., 2009; Harrison and Goni, 2010). This record provides a critical opportunity for model evaluation that should be more thoroughly exploited to gain confidence in time-dependent simulations of future change, particularly given the complex role that interacting climate change and vegetation disturbance has played in the past (e.g., Jackson et al., 2009; Marlon et al., 2009; Williams et al., 2009; Daniau et al., 2010; Dawson et al., 2011). The paleoecological record also highlights the importance of including the direct effects of changing atmospheric CO_2 levels in efforts to simulate future ecosystem functioning and plant species competition (Prentice et al., 2011; Woillez et al., 2011; Bond and Midgley, 2012; Claussen et al., 2013).

The paleoeclimatic record also reveals that past radiative climate forcing change was slower than that anticipated for the 21st century (see WGI AR5 Chapters 5, 8, and 12), but even these slower changes often drove surprisingly abrupt, nonlinear, regional-scale change in terrestrial and inland water systems (e.g., Harrison and Goni, 2010; Williams et al., 2011), as did even slower climate change during the most recent Holocene interglacial (e.g., Booth et al., 2005; Kropelin et al., 2008; Williams, J.W. et al., 2010; Williams et al., 2011). In all cases, specific periods of abrupt ecological response were regionally distinct in nature and were less synchronous for small, slow changes in forcing (e.g., during the Holocene) than for the global-scale rapid changes listed at the start of this section. State-of-the-art climate and Earth System Models (ESMs) are unable to simulate the full range of abrupt change observed in many of these periods (e.g., Valdes, 2011). Thus there is *high confidence* that these models may not capture some aspects of future abrupt climate change and associated ecosystem impacts (Leadley et al., 2010).

Frequently Asked Questions

FAQ 4.1 | How do land use and land cover changes cause changes in climate?

Land use change affects the local as well as the global climate. Different forms of land cover and land use can cause warming or cooling and changes in rainfall, depending on where they occur in the world, what the preceding land cover was, and how the land is now managed. Vegetation cover, species composition, and land management practices (such as harvesting, burning, fertilizing, grazing, or cultivation) influence the emission or absorption of greenhouse gases. The brightness of the land cover affects the fraction of solar radiation that is reflected back into the sky, instead of being absorbed, thus warming the air immediately above the surface. Vegetation and land use patterns also influence water use and evapotranspiration, which alter local climate conditions. Effective land use strategies can also help to mitigate climate change.

4.2.4. Multiple Stressors Interacting with Climate Change

The climatic and non-climatic drivers of ecosystem change need to be distinguished if the joint and separate attribution of changes to their causes is to be performed (see Chapter 18). In this section we elaborate on factors affecting ecosystems, operating simultaneously with climate change. These factors share underlining drivers with one another and with climate change to varying degrees; together they form a syndrome known as "global change." The individual effects of climate change, habitat loss and fragmentation, chemical pollution, overharvesting, and invasive alien species are increasingly well documented (Millennium Ecosystem Assessment, 2005c; Settele et al., 2010a) but much less is known about their combined consequences. Ecosystem changes may occur in cascades, where a change in one factor precipitates increased vulnerability with respect to other factors (Wookey et al., 2009) or propagates through the ecosystem as a result of species interactions (Gilman et al., 2010). Multiple stressors can act in a non-additive way (Shaw et al., 2002; Settele et al., 2010b; Larsen et al., 2011), potentially invalidating findings and interventions based on single-factor analysis. For instance, Larsen et al. (2011) demonstrated that non-additive interactions among the climate factors in a multifactor experiment were frequent and most often antagonistic, leading to smaller effects than predicted from the sum of single factor effects. Leuzinger et al. (2011) and Dieleman et al. (2012) have synthesized multifactor experiments and demonstrated that, in general, the effect size is reduced when more factors are involved, but Leuzinger et al. (2011) suggest that multifactor models tend to show the opposite tendency.

4.2.4.1. Land Use and Cover Change

Land use and cover change (LUCC) is both a cause (WGI AR5 Section 6.1.2) and a consequence of climate change. It is the major driver of current ecosystem and biodiversity change (Millennium Ecosystem Assessment, 2005b) and a key cause of changes in freshwater systems (Section 4.3.3.3). In tropical and subtropical areas of Asia, Africa, Oceania, and South America, the dominant contemporary changes are conversion of forests and woodlands to annual and perennial agriculture, grazing pastures, industrial logging, and commercial plantations, followed by conversion of savannas, grasslands, and pastures to annual agriculture (Hosonuma et al., 2012; Macedo et al., 2012). In Europe there is net conversion of agricultural lands to forest (Rounsevell and Reay, 2009; Miyake et al., 2012). Conversion of peatlands to agriculture has been an important source of carbon to the atmosphere in Southeast Asia (Limpens et al., 2008; Hooijer et al., 2010; see Section 4.3.3.3).

Contemporary drivers of LUCC include rising demand for food, fiber, and bioenergy and changes in lifestyle and technologies (Hosonuma et al., 2012; Macedo et al., 2012). By mid-century climate change is projected to become a major driver of land cover change (Leadley et al., 2010). Non-climate environmental changes such as nitrogen deposition, air pollution, and altered disturbance regimes are also implicated in LUCC. Some of the underlying drivers of LUCC are also direct or indirect drivers of climate change (Cui and Graf, 2009; McAlpine et al., 2009; Mishra et al., 2010; Schwaiger and Bird, 2010; van der Molen et al., 2011; Groisman et al., 2012); this cause-and-effect entanglement of climate change and LUCC can confound the detection of climate change and make attribution to one or the other difficult. Local-to-regional climate change was at least partly attributed to LUCC in 11 of 26 studies reviewed for this chapter, generally with *limited evidence* and *low confidence*. (Direct climate effects attributed to LUCC: Cui and Graf, 2009; Li et al., 2009; McAlpine et al., 2009; Zhang et al., 2009; Fall et al., 2010; Jin et al., 2010; Mishra et al., 2010; Schwaiger and Bird, 2010; Wu et al., 2010; Carmo et al., 2012; Groisman et al., 2012. No climate effects studied: Suarez et al., 1999; Saurral et al., 2008; Tseng and Chen, 2008; Wang et al., 2008; Cochrane and Barber, 2009; Jia, B. et al., 2009; Rounsevell and Reay, 2009; Graiprab et al., 2010; Martin et al., 2010; Wiley et al., 2010; Clavero et al., 2011; Dai et al., 2011; Gao and Liu, 2011; Viglizzo et al., 2011; Yoshikawa and Sanga-Ngoie, 2011).

LUCC (and land use itself) contributes to changes in the climate through altering the GHG concentrations in the atmosphere, surface and cloud albedos, surface energy balance, wind profiles, and evapotranspiration, among other mechanisms. The phrase "biophysical effects" is shorthand for the effect vegetation has on the climate other than through its role as a source or sink of GHGs. These effects are now well documented, significant, and are increasingly included in models of global and regional climate change. The GHG and biophysical effects of vegetation can be opposite in sign (de Noblet-Ducoudre et al., 2012) and operate at different scales. For instance, conversion of forest to non-forest generally releases CO_2 from biomass and soils to the atmosphere (causing warming globally), but may result in an increase in seasonally averaged albedo (local and global cooling, Davin et al., 2007) and a decrease in transpiration (local, but not global warming). Findell et al. (2007) concluded on the basis of model studies that the non-GHG climate impacts of LUCC were generally minor, but nevertheless significant in some regions. Brovkin et al. (2013), projecting the overall effect of LUCC on climate change for the 21st century, found LUCC to be a small driver globally, but locally important. Most global climate models suggest local average cooling effects following forest conversion to croplands and pastures (Pitman et al., 2009; Longobardi et al., 2012). Satellite observations suggest that the effect of conversion of the Brazilian savannas (*cerrado*) to pasture was to induce a local warming that was partly reversed when the pasture was subsequently converted to sugarcane (Loarie et al., 2011). Several modeling studies suggest that the global surface air temperature response to deforestation depends on the latitude at which deforestation occurs. High-latitude deforestation results in global cooling, low-latitude deforestation causes global warming, and the mid-latitude response is mixed (Bathiany et al., 2010; Davin and de Noblet-Ducoudre, 2010; van der Molen et al., 2011; Longobardi et al., 2012), with some exceptions documented for boreal forests (Spracklen et al., 2008). Boreal and tropical forests influence the climate for different reasons: boreal forests have low albedo (i.e., reflect less solar radiation, especially in relation to a snowy background; Levis, 2010; Mishra et al., 2010; Longobardi et al., 2012) and tropical forests pump more water and aerosols into the atmosphere than non-forest systems in similar climates (Davin and de Noblet-Ducoudre, 2010; Delire et al., 2011; Pielke et al., 2011). The implications of these findings for afforestation as a climate mitigation action are discussed in Section 4.3.4.5. Forests may also influence regional precipitation through biophysical effects (Butt et al., 2011; Pielke et al., 2011; see Section 4.3.3).

In summary, changes in land cover have biophysical effects on the climate, sometimes opposite in direction to GHG-mediated effects,

Box 4-1 | Future Land Use Changes

Assessment of climate change effects on terrestrial and inland freshwater ecosystems requires the simultaneous consideration of land use and cover change (LUCC). The world is undergoing important shifts in land use, driven by accelerating demand for food, feed, fiber, and fuel. The main underlying driver is the rate at which per capita consumption is growing, particularly in emerging economies (Tilman et al., 2011). Policy shifts in developed countries favoring biofuel production have also contributed (Searchinger et al., 2008; Lapola et al., 2010; Miyake et al., 2012). Agricultural commodity prices have risen and may stay high through 2020 (OECD and FAO, 2010), owing to (1) demand growth outpacing supply growth, exacerbated by climate-related crop failure (Lobell et al., 2011); (2) decline in the rate of improvement in agricultural productivity (Ray et al., 2012); (3) shortage of arable land not already under cultivation, especially in the temperate zone; (4) growing pressure on as-yet uncultivated ecosystems on soils that are potentially suitable for cultivation and that are concentrated in tropical latitudes, especially South America and Africa (Lambin and Meyfroidt, 2011); and (5) declining area under cultivation in temperate zones, mainly in developed countries. The shortage of arable land in temperate systems could put pressure on marginal or sensitive landscapes, mainly in Latin America's *cerrados* and grasslands (Brazil, Argentina) and in African savannas (Sudan, Democratic Republic of Congo, Mozambique, Tanzania, Madagascar) (Lambin and Meyfroidt, 2011).

Deforestation in developing countries correlates with the export of agricultural commodities (DeFries et al., 2010). Future LUCC remains uncertain, as it depends on economic trends and policies themselves dependent on complex political and social processes, including climate policy. By 2012, the deforestation rate in the Brazilian Amazon had declined by 77% below its 1996–2005 average (Nepstad et al., 2009; INPE, 2013) as a result of policy and market signals (Soares-Filho et al., 2010). This single trend represents a 1.5% reduction in global anthropogenic carbon emissions (Nepstad et al., 2013).

Table 4-2 | Summary of drivers and outcomes of Land Use and Land Cover Change (LUCC) scenarios associated with Representative Concentration Pathways (RCPs; Hurtt et al., 2011). RCPs are identified with the radiative forcing by 2100 (8.5, 6.0, 4.5, and 2.6 W m^{-2}) and by the name of the model used to generate the associated land use/cover scenarios (MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact), AIM (Asia-Pacific Integrated Model), GCAM (Global Change Assessment Model), and IMAGE (Integrated Model to Assess the Global Environment); see Hurtt et al. (2011) for further details).

RCP	Model and references	Key assumptions/drivers	Land use/cover outcomes
8.5	MESSAGE; Riahi et al. (2007)	• No climate change mitigation actions; radiative forcing still rising at 2100. • Strong increase in agricultural resource use driven by the increasing population (rises to 12 billion people by 2100). • Yield improvements and intensification assumed to account for most of production increases.	• Increase in cultivated land by about 305 million ha from 2000 to 2100. • Forest cover declines by 450 million ha from 2000 to 2100. • Arable land use in developed countries slightly decreased — all of the net increases occur in developing countries.
6.0	AIM; Fujino et al. (2006), Hijioka et al. (2008)	• Mitigation actions taken late in the century to stabilize radiative forcing at 6 W m^{-2} after 2100. • Population growth and economic growth. • Increasing food demand drives cropland expansion .	• Urban land use increases. • Cropland area expands. • Grassland area declines. • Total forested area extent remains constant.
4.5	GCAM; Smith and Wigley (2006), Wise et al. (2009)	• Mitigation stabilizes radiative forcing at 4.5 W m^{-2} before 2100. • Assumes that global greenhouse gas emissions prices are invoked to limit emissions and therefore radiative forcing. Emissions pricing assumes all carbon emissions are charged an equal penalty price, so reductions in land use change carbon emissions available as mitigation. • Food demand is met through crop yield improvements, dietary shifts, production efficiency, and international trade.	• Preservation of large stocks of terrestrial carbon in forests. • Overall expansion in forested area. • Agricultural land declines slightly due to afforestation.
2.6	IMAGE; van Vuuren et al. (2006), van Vuuren et al. (2007)	• Overall trends in land use and land cover are determined mainly by demand, trade, and production of agricultural products and bioenergy. • Expansion of croplands largely due to bioenergy production. • Production of animal products is met through shift from extensive to more intensive animal husbandry.	• Much agriculture relocates from high-income to low-income regions. • Increase in bioenergy production, new area for bioenergy crops near current agricultural areas. • Pasture largely constant.

Continued next page →

Box 4-1 (continued)

Each of the four main Representative Concentration Pathways (RCPs) used for future climate projections has a spatially explicit future land use scenario consistent with both the emissions scenario and the underlying associated socioeconomic scenario simulated by integrated assessment models, as well as conditions in 2005 (Hurtt et al., 2011; see also Table 4-2, Figure 4-2, Figure 4-3). In scenarios where cropland and pasture are projected to decrease, they are replaced with secondary vegetation. Tropical and boreal forest regions are both projected to undergo declining primary forest cover in most RCPs, but in RCP6.0 total forest area remains approximately constant and in RCP4.5 total forest area expands because of increased secondary forest. The extent to which primary vegetation is replaced by secondary vegetation, crops, or pasture varies between the RCPs (Figure 4-3), with no simple linear relationship between the extent of vegetation change and the level of total radiative forcing. Larger reductions in primary vegetation cover are projected in RCP8.5, owing to a general absence of proactive measures to control land cover change in that scenario. Large reductions are also projected in RCP2.6 owing to widespread conversion of land to biofuel crops (Figure 4-2). Smaller reductions are foreseen in RCP6.0 and RCP4.5, with the latter involving conservation of primary forest and afforestation as mitigation measures.

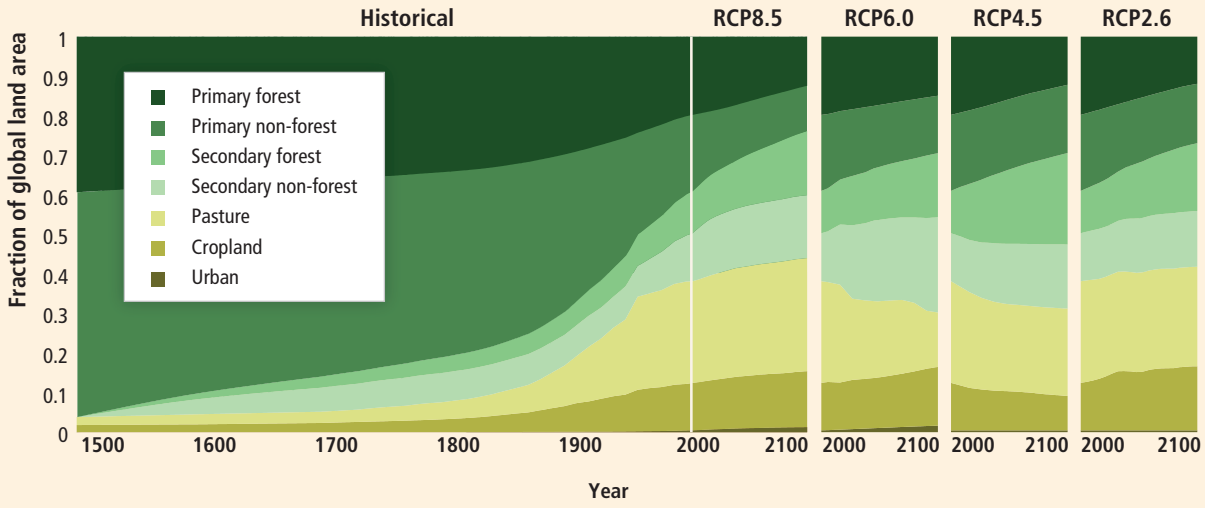


Figure 4-3 | Proportion of global land cover occupied by primary and secondary vegetation (forest and non-forest), cropland, pasture, and urban land, from satellite data and historical reconstructions up to 2005 (Klein Goldewijk et al., 2010, 2011), and from scenarios associated with the RCPs from 2005 to 2100 (Hurtt et al., 2011).

which can materially alter the net outcome of the land cover change on the global climate (*high confidence*).

4.2.4.2. Nitrogen Deposition

The global nitrogen cycle has been strongly perturbed by human activity over the past century (Gruber and Galloway, 2008; Canfield et al., 2010). Activities such as fertilizer production and fossil fuel burning currently transform 210 TgN yr^{-1} of nitrogen gas in the atmosphere into reactive forms of nitrogen (N_r) that can be readily used by plants and microorganisms in land and in the ocean, slightly more than the non-anthropogenic transformation of 203 TgN yr^{-1} (Fowler et al., 2013). Most of the transformations of anthropogenic N_r are on land (Fowler et al., 2013). The human-caused flow from land to oceans in rivers is 40 to 70 TgN yr^{-1}, additional to the estimated natural flux of 30 TgN yr^{-1} (Galloway et al., 2008; Fowler et al., 2013). Many of the sources of additional nitrogen share root causes with changes in the carbon cycle, such as increased use of fossil fuels and expansion and intensification of global agriculture. Nitrogen deposition, CO_2 concentrations, and temperatures are therefore increasing together at global scales (Steffen et al., 2011). Regional trends in nitrogen fluxes differ substantially: nitrogen fertilizer use and nitrogen deposition are stable or declining in some regions, such as Western Europe; but nitrogen deposition and its impacts on biodiversity and ecosystem functioning are projected to increase substantially over the next several decades in other regions, especially in the tropics (Galloway et al., 2008) owing to increased needs for food and energy for growing populations in emerging economies (e.g., Zhu et al., 2005).

Experiments and observations, most of which are in temperate and boreal Europe and North America, show a consistent pattern of increase in the

dominance of a few nitrogen-loving plant species and loss of overall plant species richness at nitrogen deposition loads exceeding between 5 and 20 kgN ha^{-1} yr^{-1} (Power et al., 2006; Clark and Tilman, 2008; Bobbink et al., 2010; but see Stevens, C.J. et al., 2010). Nitrogen deposition is currently above these limits in much of Europe, eastern North America, and southern Asia (Galloway et al., 2008), including in many protected areas (Bleeker et al., 2011).

The impacts of nitrogen deposition are often first manifested in freshwater ecosystems because they collect and concentrate the excess nitrogen (and phosphorus) from the land, as well as from sewage and industrial effluents. Primary production in freshwater ecosystems can be either nitrogen and phosphorus limited or both (Elser et al., 2007), but the biodiversity and capacity of freshwater ecosystems to deliver high-quality water, recreational amenity, and fisheries services is severely reduced by the addition of nutrients beyond their capacity to process them. Excessive loading of nitrogen and phosphorus is widespread in the lakes of the Northern Hemisphere (NH; Bergström and Jansson, 2006), although reduced nitrogen loading including deposition was observed between 1988 and 2003 in Sweden (Weyhenmeyer et al., 2007). The observed symptoms include a shift from nitrogen limitation of phytoplankton in lakes to phosphorus limitation (Elser et al., 2009).

Since the AR4, an increasing number of studies have models, observations, and experiments to understand and predict the interactive effects of nitrogen deposition, climate change, and CO_2 on ecosystem function. Interactions between nitrogen and other global change factors are widespread, strong, and complex (Rustad, 2008; Thompson et al., 2008; Langley and Megonigal, 2010; Gaudnik et al., 2011; Eisenhauer et al., 2012; Hoover et al., 2012; but see Zavaleta et al., 2003, for evidence of additive effects). In a study of plant-pollinator relationships, the combination of nitrogen deposition, CO_2 enrichment, and warming resulted in larger negative impacts on pollinator populations than could be predicted from the individual effects (Hoover et al., 2012). In a perennial grassland species, nitrogen limitation constrained the response to rising CO_2 (Reich et al., 2006). Broadly, the overall body of research shows that ecosystem function is mediated by complex interactions between these factors, such that many ecosystem responses remain difficult to understand and predict (Churkina et al., 2010; Norby and Zak, 2011).

In forests in many parts of the world, experiments, observations, and models suggest that the observed increase in productivity and carbon storage is due to combinations of nitrogen deposition, climate change, fertilization effects of rising CO_2, and forest management (Huang et al., 2007; Magnani et al., 2007; Pan et al., 2009; Churkina et al., 2010; Bellassen et al., 2011; Bontemps et al., 2011; de Vries and Posch, 2011; Eastaugh et al., 2011; Norby and Zak, 2011; Shanin et al., 2011; Lu et al., 2012). N deposition and rising CO_2 appear to have generally dominated in much of the NH. However, the direct effects of rising temperature and changes in precipitation may exceed nitrogen and CO_2 as key drivers of ecosystem primary productivity in a few decades time. In grasslands, however, experiments show that plant productivity is increased more by nitrogen addition (within the projected range for this century) than by elevated CO_2, also within its projected range, and that nitrogen effects increase with increasing precipitation (Lee et al., 2010).

In contrast to forests and temperate grasslands, nitrogen deposition and warming can have negative effects on productivity in other terrestrial ecosystems, such as moss-dominated ecosystems (Limpens et al., 2011). The interactions between nitrogen deposition and climate change remain difficult to understand and predict (Menge and Field, 2007; Ma et al., 2011), in part owing to shifts in plant species composition (Langley and Megonigal, 2010) and the complex dynamics of coupled carbon, nitrogen, and phosphorus cycles (Menge and Field, 2007; Niboyet et al., 2011).

Analyses using the multi-factor biodiversity change model GLOBIO3 suggest that nitrogen deposition will continue to be a significant contributing factor to terrestrial biodiversity loss in the first third of the 21st century but will be a less important factor than climate change in this period, and a much smaller driver than habitat loss due to expansion of agricultural lands (Alkemade et al., 2009). Models that explicitly take into account interactive effects of climate change and nitrogen deposition on plant communities project that nitrogen deposition impacts will continue to be important, but climate change effects will begin to dominate other factors by the middle of the 21st century (Belyazid et al., 2011).

4.2.4.3. Tropospheric Ozone

The concentration of ozone in the troposphere (the part of the atmosphere adjacent to the Earth's surface) has risen over the past 150 years from a global average of 20 to 30 ppb to 30 to 50 ppb, with high spatial and temporal variability (Horowitz, 2006; Oltmans et al., 2006; Cooper et al., 2010; WGI AR5 Figure 2.7). This is due to (1) increasing anthropogenic emissions of gases that react in the atmosphere to form ozone (Denman et al., 2007) and (2) the increased mixing of stratospheric ozone into the troposphere as a result of climate change (Hegglin and Shepherd, 2009). The key ozone precursor gases are volatile organic compounds (VOCs) and oxides of nitrogen (NO_x). Intercontinental transport of these precursors contributes to rising global background ozone concentrations, including in regions where local ozone precursor emissions are decreasing (Dentener et al., 2010). Global sources of VOC are predominantly biogenic (BVOC), especially forests (Hoyle et al., 2011).

Negative effects of the current levels of ozone have been widely documented (Mills et al., 2011). A meta-analysis of more than 300 articles addressing the effect of ozone on tree growth (Wittig et al., 2009)—focused largely on NH temperate and boreal species—concluded that current levels of tropospheric ozone suppress growth by 7% relative to preindustrial levels. Modeling studies that extrapolate experimentally measured dose-response relationships suggest a 14 to 23% contemporary reduction in Gross Primary Productivity (GPP) worldwide, with higher values in some regions (Sitch et al., 2007) and 1 to 16% reduction of Net Primary Productivity (NPP) in temperate forests (Ainsworth et al., 2012).

The mechanisms by which ozone (O_3) affects plant growth are now better known (Hayes et al., 2007; Ainsworth et al., 2012). Chronic exposure to O_3 at levels above about 40 ppb generally reduces stomatal conductance and impairs the activity of photosynthetic enzymes (The Royal Society, 2008), although in some cases ozone exposure increases stomatal conductance (Wilkinson and Davies, 2010). For the species studied,

carbon assimilation rates and leaf area are generally reduced, while respiration increases and leaf senescence is accelerated—all leading to a reduction in NPP. Conifers are less sensitive than broad-leafed species. In a modeling study, lower stomatal conductance due to O_3 exposure increased river runoff by reducing the loss of soil moisture through transpiration, but observational studies that measured runoff in relation to ozone exposure show divergent trends on this issue (McLaughlin et al., 2007; Wittig et al., 2007; Mills et al., 2009; Huntingford et al., 2011).

A modeling study (Sitch et al., 2007) suggests that the negative effects of rising O_3 on plant productivity could offset 17 to 31% of the projected increase in global carbon storage due to increasing CO_2 concentrations over the 21st century, but the possible interactive effects between CO_2 and O_3 are poorly understood (The Royal Society, 2008). Reduced stomatal conductance, widely observed under elevated CO_2, should help protect plants from ozone damage. Some chamber experiments (Bernacchi et al., 2006) and model studies (Klingberg et al., 2011) suggest this to be the case. The one plot-scale study of CO_2 and O_3 interactions in a temperate forest (Karnosky et al., 2005; Hofmockel et al., 2011) suggests that the effects of O_3 and CO_2 are not independent and may partly compensate for one another.

There is genotypic variation in plant sensitivity to O_3 (Ainsworth et al., 2012). Other than changing cultivars or species, few management actions promoting adaptation to higher levels of O_3 are currently available (Wilkinson and Davies, 2010; Teixiera et al., 2011). Research into developing ozone resistant varieties and chemical protectants against damage may provide management options in the future (Wilkinson and Davies, 2010; Ainsworth et al., 2012).

4.2.4.4. Rising Carbon Dioxide

Rising atmospheric CO_2 concentrations affect ecosystems directly and through biological and chemical processes. The consequences for the global carbon cycle are discussed in WGI AR5 Box 6.3; the discussion here focusses on impacts on terrestrial and inland water systems. Paleo records over the Late Quaternary (past Myr) show that changes in the atmospheric CO_2 content between 180 and 280 ppmv had ecosystem-scale effects worldwide (Prentice and Harrison, 2009).

In contrast to the oceans, changes in CO_2 concentrations in inland waters are influenced primarily by biological processes, such as inputs of terrestrial organic matter, particularly dissolved organic carbon (DOC), and bacterial respiration (van de Waal et al., 2010; Aufdenkampe et al., 2011). Carbon can, however, become limiting during intense algal blooms, especially in the surface waters of stratified lakes and reservoirs, and rising atmospheric CO_2 concentrations may stimulate higher algal production under these conditions (van de Waal et al., 2010). Higher CO_2 concentrations can lead to increases in the C:N and C:P ratios of phytoplankton, though the trophic consequences of this are difficult to predict because zooplankton may alter their feeding behavior to select higher quality forms of algae or increase feeding rate (Urabe et al., 2003; van de Waal et al., 2010).

Over the past 2 decades, and especially since AR4, experimental investigation of elevated CO_2 effects on plants and ecosystems has used mainly Free Air CO_2 Enrichment (FACE) techniques (Leakey et al., 2009). FACE is considered more realistic than earlier approaches using enclosed chambers, because plant community and atmospheric interactions and below-ground conditions are more like those of natural systems. Plants with a C_3 photosynthetic system, which includes most species but excludes warm-region grasses, show an increase in photosynthesis under elevated CO_2, the precise magnitude of which varies between species. Acclimation ("down-regulation") occurs under long-term exposure, leading to cessation of effects in some (Norby and Zak, 2011) but not all studies (Leakey et al., 2009). The C_4 photosynthetic system found in most tropical grasses and some important crops is not directly affected by elevated CO_2, but C_4 plant productivity generally increases under elevated CO_2 because of increased water use efficiency (WUE). Transpiration is decreased under elevated CO_2 in many species, due to reduced opening of stomatal apertures, leading to greater WUE (Leakey et al., 2009; Leuzinger and Körner, 2010; De Kauwe et al., 2013). Increasing WUE is corroborated by studies of stable carbon isotopes (Barbosa et al., 2010; Koehler et al., 2010; Silva et al., 2010; Maseyk et al., 2011). The WUE increase does not acclimate to higher CO_2 in the medium term, that is, over several years (Leakey et al., 2009). Satellite observations from 1982–2010 show an 11% increase in green foliage cover in warm, arid environments (where WUE is most important) after correcting for the effects of precipitation variability (Donohue et al., 2013); gas exchange theory predicts 5 to 10% greening resulting from rising CO_2 over this period.

The interactive effects of elevated CO_2 and other global changes (such as climate change, nitrogen deposition, and biodiversity loss) on ecosystem function are extremely complex. Generally, nitrogen use efficiency is

Frequently Asked Questions

FAQ 4.2 | What are the non–greenhouse gas effects of rising carbon dioxide on ecosystems?

Carbon dioxide (CO_2) is an essential building block of the process of photosynthesis. Simply put, plants use sunlight and water to convert CO_2 into energy. Higher CO_2 concentrations enhance photosynthesis and growth (up to a point), and reduce the water used by the plant. This means that water remains longer in the soil or recharges rivers and aquifers. These effects are mostly beneficial; however, high CO_2 also has negative effects, in addition to causing global warming. High CO_2 levels cause the nitrogen content of forest vegetation to decline and can increase their chemical defenses, reducing their quality as a source of food for plant-eating animals. Furthermore, rising CO_2 causes ocean waters to become acidic (see FAQ 6.3), and can stimulate more intense algal blooms in lakes and reservoirs.

increased under higher CO_2 (Leakey et al., 2009) although, in some tree FACE experiments, productivity increases as a result of enhanced CO_2 if sustained by increased nitrogen uptake rather than increased nitrogen use efficiency (Finzi et al., 2007). In one 10-year temperate grassland experiment in Minnesota, elevated CO_2 halved the loss of species richness expected from nitrogen addition (Reich, 2009), whereas no such benefit was reported for an alpine grassland in France (Bloor et al., 2010) or a Danish heathland ecosystem (Kongstad et al., 2012).

Elevated CO_2 can affect plant response to other stresses, such as high temperature (Lloyd and Farquhar, 2008) and drought. Ozone exposure decreases with lower stomatal conductance (Sitch et al., 2007). In savannas, faster growth rates under higher CO_2 can allow woody plants to grow tall enough between successive fires to escape the flames (Bond and Midgley, 2001; Scheiter and Higgins, 2009). Differential species responses to elevated CO_2 appear to be altering competition (Dawes et al., 2011), for example, increasing the likelihood of faster-growing species such as lianas out-competing slower-growing species such as trees (Mohan et al., 2006; Potvin et al., 2007; Lewis et al., 2009a).

Experimental studies have shown that elevated CO_2 leads to increased leaf C:N ratios in woody plants, forbs, and C_3 grasses (but not C_4 grasses), which may decrease their quality as food and increase herbivorous insect feeding rates and changes to their density and community structure (Sardans et al., 2012). Plants may also become more toxic to herbivores under elevated CO_2 levels, through increased concentrations of carbon- and nitrogen-based defenses (Lindroth, 2010; Cavagnaro et al., 2011).

Our understanding of ecosystem responses to elevated CO_2 is incomplete in some respects. The majority of FACE experiments apply upper CO_2 concentrations of approximately 550 ppmv, which is below the concentrations projected by 2100 under higher emissions scenarios. The physiology of photosynthesis suggests that direct CO_2 effects saturate at levels of approximately 700 ppmv (Long et al., 2004). Most elevated CO_2 experiments impose a sudden increase of CO_2 concentration as opposed to the gradual rise experienced in reality. Most large-scale FACE experiments have been conducted in temperate locations (e.g., Hickler et al., 2008); there are currently no large-scale tropical or boreal FACE experiments. The magnitude of CO_2 effects decreases as the spatial scale of study increases (Leuzinger et al., 2011). The scale of controlled experiments is limited to approximately 100 m^2. Extrapolation to larger scales ignores large-scale atmospheric feedbacks (Körner et al., 2007) and catchment-scale hydrological effects (see Box CC-VW). Overall, there is *medium confidence* (*much evidence*, *medium agreement*) that increases in CO_2 up to about 600 ppm will continue to enhance photosynthesis and plant water use efficiency, but at a diminishing rate.

CO_2 effects are a first-order influence on model projections of ecosystem and hydrological responses to anthropogenic climate change (Sitch et al., 2008; Lapola et al., 2009; Friend et al., 2013). The direct effect of CO_2 on plant physiology, independent of its role as a GHG, means that assessing climate change impacts on ecosystems and hydrology solely in terms of global mean temperature rise (or equivalently, expressing GHG effects solely in terms of radiative forcing) is an oversimplification (Huntingford et al., 2011; Betts et al., 2012). A 2°C rise in global mean temperature, for example, may have a different net impact on ecosystems depending on the change in CO_2 concentration accompanying the rise (e.g., Good et al., 2011a). A high climate sensitivity and/or a higher proportion of non-CO_2 GHGs would imply a relatively low CO_2 rise at 2°C global warming, so the offsetting effects of CO_2 fertilization and increased water use efficiency would be smaller than for low climate sensitivity and/or a lower proportion of non-CO_2 GHGs.

4.2.4.5. Diffuse and Direct Radiation

The quantity and size distribution of aerosols in the atmosphere alters both the amount of solar radiation reaching the Earth's surface and the proportions of direct versus diffuse radiation. In some regions, direct radiation has been reduced by up to 30 W m^{-2} over the industrial era, with an accompanying increase in diffuse radiation of up to 20 W m^{-2} (Kvalevåg and Myhre, 2007). The global mean direct and diffuse radiation changes due to aerosols are −3.3 and +0.9 W m^{-2}, respectively (Kvalevåg and Myhre, 2007). For a constant total radiation, an increased fraction received as diffuse radiation theoretically increases net photosynthesis because a smaller fraction of the vegetation canopy is light-saturated, making photosynthesis more light efficient at the canopy scale (Knohl and Baldocchi, 2008; Kanniah et al., 2012). In a global model that included this effect, an increase in diffuse fraction of solar radiation due to volcanic and anthropogenic aerosols and cloud cover was simulated to lead to approximately a 25% increase in the strength of the global land carbon sink between 1960 and 1999; however, under a scenario of climate change and decreased anthropogenic aerosol concentration, this enhancement declined to near zero by the end of the 21st century (Mercado et al., 2009), All RCPs project decreased aerosol concentrations due to air quality protection measures, as already seen in some countries. The influence of the form of radiation on plant growth and the land carbon budget is a potentially important unintended consequence of solar radiation management schemes that involve the injection of aerosols into the stratosphere to reduce radiant forcing (see WGI AR5 Section 7.7), but this topic is at present insufficiently researched for adequate assessment.

4.2.4.6. Invasive and Alien Species

Since the IPCC AR4, the number of observations of the spread and establishment of alien species attributed to climate change has increased for several taxa (e.g., Walther et al., 2009) and for particular areas, including mountain tops and polar regions (McDougall et al., 2011; Chown et al., 2012). Species invasions have increased over the last several decades (*very high confidence*), and the aggressive expansion of plant and animal species beyond their historical range is having increasingly negative impacts on ecosystem services and biodiversity (*high confidence*; Brook, 2008; Burton et al., 2010; McGeoch et al., 2010; Simberloff et al., 2013). Climate change will exacerbate some invasion impacts and ameliorate others (Peterson et al., 2008; Bradley et al., 2009; Britton et al., 2010; Bellard et al., 2013). Although there is increasing evidence that some species invasions have been assisted by climate change, there is *low confidence* that species invasions have in general been assisted by recent climatic trends because of the overwhelming importance of human-facilitated dispersal in mediating invasions. The spread of alien species has several causes, including habitats made favorable by climate change (Walther et al., 2009), deliberate species

Frequently Asked Questions

FAQ 4.3 | Will the number of invasive alien species increase as a result of climate change?

Some invasive plants and insects have already been shown to benefit from climate change and will establish and spread into new regions (where they are "aliens"), once they are introduced. The number of newly arrived species and the abundance of some already established alien species will increase because climate change will improve conditions for them. At the same time, increasing movement of people and goods in the modern world, combined with land use changes worldwide, increases the likelihood that alien species are accidentally transported to new locations and become established there. There are many actions that can be taken to reduce, but not eliminate, the risk of alien species invasions, such as the treatment of ballast water in cargo ships and wood products, strict quarantine applied to crop and horticultural products, and embargos on the trade and deliberate introduction of known invader species. Some invasive species will suffer from climate change and are expected to decrease in range and population size in some regions. Generally, increased establishment success and spread will be most visible for those alien species that have characteristics favored by the changing climate, such as those that are drought tolerant or able to take advantage of higher temperatures.

transfer, and accidental transfer due to increased global movement of goods.

In most cases climate change increases the likelihood of the establishment, growth, spread, and survival of invasive species populations (Dukes et al., 2009; Walther et al., 2009; Bradley et al., 2010; Huang et al., 2011; Chown et al., 2012). Some degree of climate/habitat match has been found to be a prerequisite of establishment success across seven major plant and animal groups (Hayes and Barry, 2008). A range of alien species responses and local consequences are expected (e.g., Rahel and Olden, 2008; Frelich et al., 2012; Haider et al., 2012; West et al., 2012). Invasive species, compared to native species, may have traits that favor their survival, reproduction, and adaptation under changing climates; invasive plants in particular tend to have faster growth rates and are particularly favored when resources are not limited (*medium* to *high confidence*; van Kleunen et al., 2010; Willis, C.G. et al., 2010; Buswell et al., 2011; Davidson et al., 2011; Zerebecki and Sorte, 2011; Haider et al., 2012; Matzek, 2012). Some invasive plants are more drought tolerant (Crous et al., 2012; Matzek, 2012; Perry et al., 2012), and on average they have higher overall metabolic rates, foliar nitrogen concentrations, and photosynthetic rates than their native counterparts (Leishman et al., 2007).

Extreme climate events provide opportunities for invasion by generating disturbances and redistributing available resources (Diez et al., 2012) and changing connectivity between different ecosystems. Current warming has already enabled many invasive alien species, including plant, vertebrate, invertebrate, and single-cell taxa, to extend their distributions into new areas (*high confidence* for plants and insects; Walther et al., 2009; Smith et al., 2012). However, population declines and range contractions are predicted for some invasive species in parts of their ranges (Bradley et al., 2009; Sobek-Swant et al., 2012; Taylor et al., 2012; Bertelsmeier et al., 2013). The expansion of invasive species in some areas and contraction in others will contribute to community reorganization and the formation of novel ecosystems and interactions in both terrestrial and freshwater habitats (*high confidence*; e.g., Britton et al., 2010; Kiesecker, 2011; Martinez, 2012; see also Section 4.3.2.5). For example, invasive grasses may be favored over native ones with increasing temperatures (Parker-Allie et al., 2009; Chuine et al., 2012; Sandel and Dangremond, 2012).

In a few cases, benefits to biodiversity and society may result from the interactive effects of climate change and invasive species, such as increases in resources available to some threatened species (Caldow et al., 2007), forest structural recovery (Bolte and Degen, 2010), and available biomass for timber and fuel (van Wilgen and Richardson, 2012). The effect of invasions on net changes in carbon stocks are situation specific and may be either positive or negative (Williams, A.L. et al., 2007). Rising CO_2 levels will increase the growth rates of most invasive plant species (Mainka and Howard, 2010; but see Section 4.2.4.4). The effectiveness of invasive alien species management for sequestering carbon is uncertain and context specific (Peltzer et al., 2010). Longer term, indirect effects of invasive alien species will be more important than direct, short-term effects, for instance, as a result of changes in soil carbon stocks and tree community composition (*low* to *medium confidence*; Peltzer et al., 2010).

Synergistic interactions occur between climate change and invasive alien species, along with landscape change, habitat disturbance, and human-facilitated breakdown of dispersal barriers (Brook et al., 2008; Angeler and Goedkoop, 2010; Bradley et al., 2010; Winder, M. et al., 2011). Climate change and invasive alien plant species generally increase the risk and intensity of fire, and the interaction is being reported more frequently as a direct result of higher temperatures and increased invasive plant biomass (*high confidence*; Abatzoglou and Kolden, 2011). In freshwater systems, alien species establishment and survival, species interactions, and disease virulence will change as a result of changes in frequency of high-flow events, increasing water temperature, water properties, and water demand (*medium confidence*; Schnitzler et al., 2007; Rahel and Olden, 2008; Britton et al., 2010).

A range of climate change-related variables (extreme events and changes in precipitation, temperature, and CO_2) will continue to exacerbate the establishment and spread of pests, vectors, and pathogens and negatively impact production systems (*medium confidence*; Robinet and Roques, 2010; Clements and Ditommaso, 2011). Warming has contributed to the spread of many invasive insect species, such as the mountain pine

bark beetle, and resulted in forest destruction (*high confidence*; Raffa et al., 2008). The interactions between crop growth, climate change, and pest or pathogen dynamics are difficult to predict (West et al., 2012). Management strategies may become less effective as a consequence of the decoupling of biocontrol relationships and less effective mechanical control as biomass and/or population size of invasive species increases (*low* to *medium confidence*; Hellmann et al., 2008).

4.3. Vulnerability of Terrestrial and Freshwater Ecosystems to Climate Change

The vulnerability of ecosystems to climate change, that is, their propensity to be adversely affected, is determined by the sensitivity of ecosystem processes to the particular elements of climate undergoing change and the degree to which the system (including its coupled social elements) can maintain its structure, composition, and function in the presence of such change, either by tolerating or adapting to it. Tolerance and adaptability both interact with exposure, which in the case of terrestrial and freshwater ecosystems means the magnitude and rate of climate change relative to ranges of climatic conditions and rates of change under which the ecosystem developed and its organisms evolved. Chapter 19 provides a full discussion on vulnerability concepts.

4.3.1. Changes in the Disturbance Regime

The species composition at a given location is determined by three considerations: the ability of species to reach the location; the physiological tolerance of the species in relation to the range of conditions experienced there; and interactions with other species, including competitors, symbionts, predators, prey, and pathogens. Occasional disturbances relieve competition, create opportunities for the establishment and success of less dominant species, and may facilitate dispersal. Moderate disturbance is thus important in maintaining diversity and ecosystem function (Connell, 1978). Exposure to disturbances keeps tolerance of disturbance in the population high. Fire, floods, and strong winds are all examples of biodiversity-sustaining climate disturbances, provided that their frequency and intensity do not deviate greatly above or below the regime to which the species are adapted. Average environmental conditions may be less of a determinant of species range and abundance than the extreme conditions, such as the occurrence of exceptionally cold or hot days or droughts exceeding a certain duration (Zimmermann et al., 2009). The projected changes in probability of extremes are typically disproportionately larger than the projected changes in the mean (see IPCC, 2012; but also Diffenbaugh et al., 2005). Biotic disturbances, such as pest and pathogen outbreaks are also often implicated in ecosystem change, and may be enabled by climate change.

It is suggested that ecosystem regime shifts resulting from climate change (alone or in interaction with other factors) will often be triggered by changes in the disturbance regime, rather than by physiological tolerance for the mean conditions (Thonicke et al., 2001). A "disturbance regime" refers to the totality of different types of disturbance events in a system, each characterized by its probability of occurrence, intensity, and other relevant attributes, such as its seasonal pattern. A corollary is that disturbance-related change is abrupt rather than gradual. Change in the fire disturbance regime is emerging as a key proximal mechanism and early indicator of terrestrial ecosystem change (Girardin et al., 2009; Johnstone et al., 2010). Changes in the fire regime have in some cases been attributed to climate change (Littell et al., 2009). Regional trends in fire occurrence have been observed since 2000 (Giglio et al., 2013), but interpreting their significance requires a longer term perspective (e.g., Bergeron et al., 2010).

4.3.2. Observed and Projected Change in Ecosystems

This section highlights key observed changes in terrestrial and freshwater ecosystems over the recent past, as well as changes projected during the 21st century. For observations, we assess the degree of confidence that change has been detected, and separately the confidence we have in attributing the change to climate change (Figure 4-4). Confidence in detection is considered to be *very high* when there is *high agreement* between many independent studies, species, ecosystems, or regions and where there is *robust evidence* that the changes over time are statistically significant (see Chapter 18; Mastrandrea et al., 2010). Note that a slightly different definition of detection is used here than in Chapter 18, because detection here is based solely on the presence of a temporal trend and does not attempt to distinguish natural from climate-related variation. Confidence in attribution to climate change is *very high* when three tests are satisfied: changes correspond to a sound mechanistic understanding of responses to climate change; the time series of observations is sufficiently long to detect trends correlated with climate change; and confounding factors can be accounted for or are of limited importance. In the sections that provide the details of the assessment of detection and attribution, estimated levels of confidence are given even in cases where the capacity for detection or attribution capacity is *low* or *very low*, because changes in these ecosystem properties or processes could have large impacts on biodiversity or ecosystem services at regional to global scales. In all cases the estimates of confidence levels are based on global and cross-taxon assessments, so the positioning may be different for specific taxa or regions. Some of the sections include assessments of model-based projections of future change; the confidence assessment of detection and attribution does not extend to these.

A key message arising from the analysis of *detection* and *attribution* is that climate impacts on the functioning of organisms and ecosystems are clearest when temperature is a principal driver, changes are relatively rapid, and confounding factors play a small role. At one end of the spectrum, the large warming signal over the last several decades in much of the Arctic tundra combined with minimal human impacts is associated with *high confidence* in detection of an increase in shrubs and permafrost thawing and *high confidence* in the attribution to climate warming (Section 4.3.3.1.1). Likewise, the phenology of most organisms is sensitive to temperature, confounding effects are often small, and the response is rapid, leading to *high confidence* in detection and attribution of changes in phenology to warming (Section 4.3.2.1). At the opposite end of the spectrum, species extinctions are very difficult to attribute to climate change (Section 4.3.2.5), in part because other factors dominate recent extinctions. This does not mean that climate has not played an important contributing role; indeed it has been argued that the low level of confidence in attribution is due to the lack of studies looking for climate signals in extinctions (Cahill et al., 2013). Similarly there is

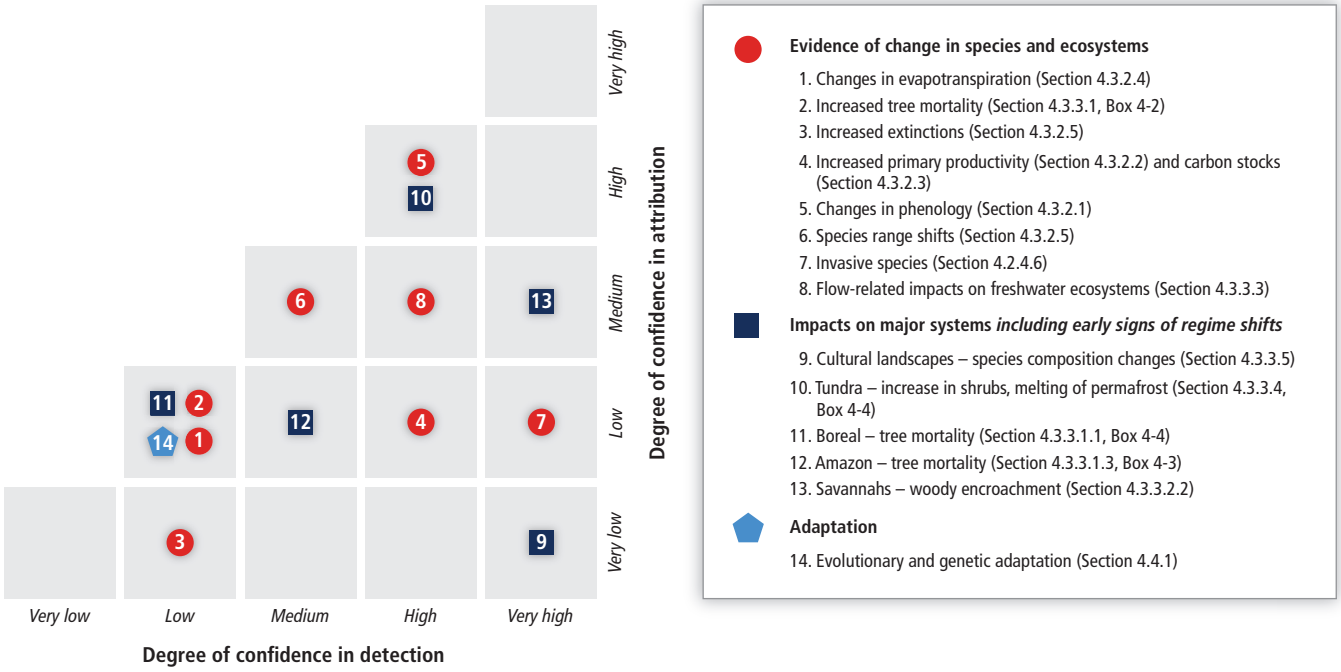


Figure 4-4 | Confidence in detection of change and attribution of observed responses of terrestrial ecosystems to climate change. Confidence levels are based on expert judgment of the available literature following the IPCC uncertainty guidance (Mastrandrea et al., 2010), attribution criteria outlined in Chapter 18, and detection criteria defined in the text. The symbols in the figure represent global and cross-taxon assessments; the positioning may be different for specific taxa or regions. Details of the assessments that were used in positioning each of the points can be found in the sections given in parentheses.

very good evidence that species composition is changing in cultural landscapes, but the important role of other factors, for example, land management and nitrogen deposition, makes attribution of a contribution to recent warming difficult. This analysis indicates that responses in most species and ecosystem levels will become more apparent over time because (1) observed organism-level changes will have long-term impacts on ecosystem functioning (*high confidence*; Sections 4.3.2.1, 4.3.2.5, 4.3.3) and (2) warming signals can be detected in ecosystems where the recent warming has been strong and confounding factors are minimal. In addition, the absence of observed changes does not preclude confident projections of future change for three reasons: climate change projected for the 21st century substantially exceeds the changes experienced over the past century in medium to high scenarios (all but RCP2.6); ecosystem responses to climate change may be nonlinear; and change may be apparent only after considerable time lags (Jones et al., 2009).

4.3.2.1. Phenology

Further evidence from ground-based and satellite studies, focused mainly on the NH (Northern Hemisphere), supports the AR4 conclusion that shifts in phenology have occurred over recent decades. "Spring advancement"—earlier occurrence of spring events, such as breeding, bud burst, breaking hibernation, flowering, migration—is seen in hundreds of plant and animal species in many regions (Menzel et al., 2006; Cleland et al., 2007; Parmesan, 2007; Primack et al., 2009; Cook et al., 2012a; Peñuelas et al., 2013), although magnitudes of change vary considerably and some species show no change (Parmesan, 2007). Apparent discrepancies between two estimates of overall NH spring advancement noted in AR4 (-2.3 days per decade, Parmesan and Yohe, 2003; -5.1 days per decade, Root et al., 2003) are largely resolved when methodological differences are accounted for, particularly the inclusion of species that do not show phenological changes (Parmesan, 2007). A combined analysis of 203 species suggests NH spring advancement of -2.8 ± 0.35 days per decade (Parmesan, 2007).

4.3.2.1.1. Plants

Spring advancement is seen across the NH including North America (e.g., Cook et al., 2008, 2012b), Europe (e.g., Menzel et al., 2006; Cook et al., 2012b), Asia (e.g., Primack et al., 2009; Ma and Zhou, 2012), and the High Arctic (Høye et al., 2007). Changes are generally larger at higher latitudes. A meta-analysis indicates mean NH spring advancement of -1.1 ± 0.16 days per decade for herbs and grasses (85 species), -1.1 ± 0.68 days per decade for shrubs (6 species), and -3.3 ± 0.87 days per decade for trees (16 species), over a record period of 35 to 132 years, depending on the study. The warming trends detected in the well-mixed surface waters (epilimnion) of many lakes in North America, Eurasia, and Africa (Adrian et al., 2009) are associated with the earlier onset of spring phytoplankton blooms (Winder and Schindler, 2004; Winder and Sommer, 2012). Satellite data also indicate a general tendency of spring advancement, though there is variation between satellite studies, especially at local scales, due to the use of different instruments and methods (e.g., White et al., 2009). A study using the Advanced Very High Resolution Radiometer (AVHRR) suggests that for vegetation between 30°N and 80°N, the start of the growing season advanced by -5.2 days

between 1999 and 1982 and advanced a further -0.2 days by 2008; while the growing season end was delayed by 6.6 days between 1982 and 2008 (Jeong et al., 2011). Studies with a more recent satellite instrument, the Moderate Resolution Imaging Spectrometer (MODIS), also show spring advancement (e.g., Ahl et al., 2006). The relatively short duration of satellite observations makes trend detection particularly sensitive to the choice of analysis period.

4.3.2.1.2. Animals

Many new studies provide further evidence of changes in animal phenology (e.g., amphibians: Kusano and Inoue, 2008; Phillimore et al., 2010; birds: Pulido, 2007; Thorup et al., 2007; mammals: Adamik and Kral, 2008; Lane et al., 2012; insects: Robinet and Roques, 2010; freshwater plankton: Adrian et al., 2009). Changes in breeding phenology are reported from various regions and different taxa (e.g., Parmesan, 2006, 2007; Post et al., 2008; Primack et al., 2009). In the NH several studies show advancements of egg laying dates in birds (e.g., Parmesan, 2007: -3.7 ± 0.7 days per decade, in 41 species). In contrast, a delay of the mean breeding date by 2.8 to 3.7 days between 1950 and 2004 was seen for two of nine seabirds in the Eastern Antarctic, linked to decreased sea ice extent (Barbraud and Weimerskirch, 2006). Spring arrival dates have advanced for many migratory birds (e.g., Thorup et al., 2007). Patterns of changes in autumn migration in birds are mostly not consistent (delayed, advanced, no change) across analyzed species and regions and appear to be highly related to non-climatic variables (e.g., Sokolov, 2006; Adamik and Pietruszkova, 2008).

A large body of evidence therefore shows that, in NH temperate, boreal, and Arctic regions, spring advancement has occurred in many plant and animal species over the last several decades (*high confidence* due to *robust evidence* but only *medium agreement* when examined across all species and regions; Figure 4-4).

Understanding of the drivers of phenological change has also improved further since AR4. Many observational studies find a correlation with higher temperatures (Cook et al., 2012a). Experimental manipulation generally supports this (e.g., plants: Cleland et al., 2012; bird egg-laying: Visser et al., 2009; insects: Musolin et al., 2010; Kollberg et al., 2013). Some individual studies find good agreement between experimental warming and *in situ* observations (e.g., Gunderson et al., 2012) although a meta-analysis suggests that experiments can substantially under-predict advances in the timing of flowering and leafing of plants in comparison with observational studies (Wolkovich et al., 2012). Observational data can also be affected by methodological issues; for example, flipper-tagging of penguins can alter their migratory behavior (Saraux et al., 2011). Rates of warming across a season may also be important (Schaper et al., 2012). Models can be used to explain relationships between observed phenological changes and environmental variables. For example, a model based on water temperature captured the observed temporal and spatial variation in *Daphnia* phenology in NH lakes (Straile et al., 2012). Other environmental factors related to temperature, such as timing of snowmelt, snow cover, and snow depth, can play a role. Snowmelt changes led to earlier flowering and appearances of plants and arthropods in Greenland between 1996 and 2005 (Høye et al., 2007) and earlier flowering in an alpine plant in the Rocky Mountains, USA, between 1975 and 2008 (Hülber et al., 2010; Lambert et al., 2010). Earlier snowmelts decreased floral resources and hence affected insect population dynamics in mountain ranges in the USA in the years 1980, 1985, 1986, and 1989 (Boggs and Inouye, 2012). In Colorado, USA, the yellow-bellied marmot emerged earlier from hibernation due to snowmelts becoming earlier over 1976–2008 (Ozgul et al., 2010) while in Alberta, Canada, Columbian ground squirrels emerged later over 1992–2012 owing to delayed snowmelts associated with increased late-season snowstorms (Lane et al., 2012). Delayed emergence from hibernation was associated with decreased population growth rate (Lane et al., 2012). Food availability can be important; for example, in the Yukon area, Canada, the date of giving birth in North American squirrels (*Tamiascurus hudsonicus*) advanced by an average of -18 days over the period 1989–1998, coinciding with increasing abundance of white spruce cones, their major food source (Réale et al., 2003).

Phenological response can differ with migration strategy in birds, for example short-distance migrants show greater advancements in spring arrivals than long distant migrants (e.g., Saino et al., 2009; but see Parmesan, 2006 for different patterns). In a temperate region (Massachusetts, USA), declining sizes of populations and migrating cohorts of North American Passerine birds account for a large part of the variation in migration times between 1970 and 2002 (Miller-Rushing et al., 2008). The remaining variation was explained by climatic variables, migration distance, and date. The variation in bird migration phenology change can also be related to differing patterns of feather changes during moulting times, food availability at stop-over places, and differing health conditions of individual species (Gordo, 2007).

Although a number of non-climatic influences on phenology are also identified, an increased number of observational and experimental studies, across many organism types, suggest that warming has contributed to the overall spring advancement observed in the NH (*high confidence* due to *high agreement* and *medium evidence*).

4.3.2.2. Primary Productivity

Primary production, the process of plant growth, is fundamental to the global carbon cycle (see Section 4.3.2.3) and underpins provisioning ecosystem services such as food, timber, and grazing. Trends in the amount, seasonal timing, variability, location, and type of primary production are therefore important indicators of ecosystem function. Well-established theory, experimentation, and observation all agree that primary production is directly sensitive to most aspects of climate change, is indirectly affected via the effects of climate on pests and diseases, and is responsive to many of the other changes simultaneously taking place in the world, such as described in Section 4.2.4. The diverse and frequently nonlinear form of responses to the factors influencing primary production, combined with the complexity of interactions between them, means that at a given location the net outcome can be an increase, no change, or a decrease in productivity.

The concentration of CO_2 in the atmosphere shows clear patterns in space and time largely related to the primary productivity of the land and oceans. The contribution by terrestrial ecosystems to these patterns can be estimated using isotope measurements, emission databases, and

models (Canadell et al., 2007). It consists of a sink term, due to increased net ecosystem production, plus a source term due to land use change. During the decade 2000–2009, land net primary productivity at the global scale continued to be enhanced about 5% relative to the estimated preindustrial level, leading to a land sink of 2.6 + 1.2 PgC yr^{-1} (these values are from WGI AR5 Section 6.3.2.6; the uncertainty range is 2 standard deviations; for the primary literature see also Raupach et al., 2008; Le Quéré et al., 2009). The net uptake of carbon by the land is highly variable year to year, mainly in response to climate variation and major volcanic eruptions (Peylin et al., 2005; Sitch et al., 2008; Mercado et al., 2009). Given the uncertainty range, it is not possible to conclude whether the rate of carbon uptake by the residual land sink has increased or decreased over the past 2 decades (Raupach et al., 2008; WGI AR5 Section 6.3.2.6). Coupled Model Intercomparison Project Phase 5 (CMIP5) model projections, using the RCP scenarios, suggest that the rate of net carbon uptake by terrestrial ecosystems will decrease during the 21st century except under the RCP4.5 scenario, and by the greatest amount under RCP8.5. There is greater uncertainty between models than between scenarios; in some models terrestrial ecosystems become a net source of CO_2 to the atmosphere (WGI AR5 Section 6.4.3.2, especially Figure 6.26).

It is possible to downscale the land sink estimate continentally, using inversion modeling techniques and the growing network of precision atmospheric observations. There is *high agreement* and *medium evidence* that the net land uptake in natural and semi-natural terrestrial ecosystems is broadly distributed around the world, almost equally between forested and non-forested ecosystems, but is offset in the tropics by a large carbon emission flux resulting from land use change, principally deforestation (Pan et al., 2011).

The observed trends in Normalized Difference Vegetation Index (NDVI), a satellite proxy for primary productivity, are discussed under various ecosystem-specific discussions above and below. In some cases the trends are sufficiently strong and consistent to support a confident statement about the underlying phenomenon, but in many cases they are not. This may mean that no change has occurred, or simply reflect inadequacies in the indicator, method of analysis, and length of the record in relation to the high interannual variability. AR4 reported a trend of increasing seasonally accumulated NDVI ("greening") at high northern latitudes (Fischlin et al., 2007; based on Sitch et al., 2007), but subsequent observations show a lower rate and no geographical uniformity (Goetz et al., 2007). More than 25% of high-latitude North American forest areas, excluding areas recently disturbed by fire, showed a decline in greenness and no systematic change in growing season length, particularly after 2000 (Goetz et al., 2007). NDVI trend analyses in rangelands show varying patterns around the world, with substantial disagreement between studies (Millennium Ecosystem Assessment, 2005a; Bai et al., 2008; Beck, H.E. et al., 2011; Fensholt et al., 2012). There is agreement that the Sahel showed widespread NDVI increase between the mid-1980s and about 2000, along with an increase in rainfall, but no consensus on whether the detected signal represents increased productivity by grasses, trees, or herbs; and to what degree it reveals land management efforts or responses to climate (Anyamba and Tucker, 2005; Prince et al., 2007; Hellden and Tottrup, 2008; Seaquist et al., 2009). In the period 2000–2009 no NDVI trend was apparent in the Sahel (Samanta et al., 2011).

Tree rings record changes in tree growth over approximately the past millennium. Many tree ring records show accelerated tree growth during much of the 20th century (Briffa et al., 2008), which often correlates with rising temperature. Variations in tree ring width, density, and isotopic composition arise from many factors, including temperature, moisture stress, CO_2 fertilization, N deposition, and O_3 damage, but also stand structure and management. Direct CO_2 effects, inferred from the ring record once the effects of drought and temperature have been accounted for, have been proposed for approximately 20% of the sites in the International Tree Ring Data Base (Gedalof and Berg, 2010) and studied in detail at some sites (Koutavas, 2008). Since the 1980s, a number of tree ring records show a decline in tree growth (Wilson et al., 2007). Several possible causes have been suggested for this, including increasing water stress and O_3 damage; but the most recent rings in most published tree ring chronologies date from before the 1990s (Gedalof and Berg, 2010), so tree ring-based conclusions for the past 2 decades are based on a relatively small body of evidence and may therefore be biased. Recent tree ring studies were often specifically designed to examine growth in response to environmental changes (Gedalof and Berg, 2010) and may therefore not be representative of global tree growth. Direct repeated measurements of tree girth increment in forest monitoring plots (discussed in Section 4.3.2.3) are an alternate data source for recent decades.

Primary production in freshwater lakes has been observed to increase in some Arctic (Michelutti et al., 2005) and boreal lakes, but to decrease in Lake Tanganyika in the tropics (O'Reilly et al., 2003). In both cases the changes were attributed by the authors to climate change.

In summary, there is *high confidence* that net terrestrial ecosystem productivity at the global scale has increased relative to the preindustrial era. There is *low confidence* in attribution of these trends to climate change. Most studies speculate that rising CO_2 concentrations are contributing to this trend through stimulation of photosynthesis, but there is no clear, consistent signal of a climate change contribution (Figure 4-4).

4.3.2.3. Biomass and Carbon Stocks

The forest biomass carbon stock can be estimated from the routine forest monitoring that takes place for management and research purposes. Forest inventories were generally designed to track timber volumes; inferring total biomass and ecosystem carbon stocks requires further information and assumptions, which make absolute values less certain, but have a lesser effect on trend detection. Forest inventory systems are well developed for NH temperate and boreal forest (Nabuurs et al., 2010; Ryan et al., 2010; Wang, B. et al., 2010). Data for tropical and Southern Hemisphere forests and woodlands also exist (Maniatis et al., 2011; Tomppo et al., 2010) but are typically less available and comprehensive (Romijn et al., 2012). More and better data may become available as a result of advances in remote sensing (e.g., Baccini et al., 2012) and increased investment in forest monitoring through initiatives such as the Reduced Emissions from Deforestation and Degradation (REDD) of the United Nations Framework Convention on Climate Change (UNFCCC).

Forests have increased in biomass and carbon stocks over the past half century in Europe (Ciais et al., 2008; Luyssaert et al., 2010) and the USA

(Birdsey et al., 2006). Canadian managed forests increased in biomass only slightly during 1998–2008, because growth was offset by significant losses due to fires and beetle outbreaks (Stinson et al., 2011). Several dozen sites across the moist tropics have been monitored to estimate forest biomass changes. In the Amazon (Phillips et al., 2009) forest biomass has generally increased in recent decades, dropping temporarily after a drought in 2005. Globally, for the period 2000–2007, recently undisturbed forests are estimated to have withdrawn 2.30 ± 0.49 PgC yr^{-1} from the atmosphere, while formerly cleared tropical forests, now regrowing, withdrew an additional 1.72 ± 0.54 PgC yr^{-1} (Pan et al., 2011). The global terrestrial carbon sink is partly offset by the losses of forest carbon stocks to the atmosphere through land use change, largely in the tropics, of 1.1 ± 0.8 PgC yr^{-1} (2000–2009, WGI AR5 Section 6.3.2.6).

The carbon stock in global soils, including litter and peatlands is 1500 to 2400 PgC, with permanently frozen soils adding another 1700 PgC (Davidson and Janssens, 2006). The soil carbon stock is thus more than 10 times greater than the carbon stock in forest biomass (Kindermann et al., 2008). Changes in the size of the soil carbon stock result from changes in the net balance of inputs and losses over a period of many years. Inputs derive from primary production, discussed in Section 4.3.2.2, and are mostly modestly increasing under climate change. Losses result principally through the respiration of soil microbes, which increases with increasing temperature. The present and future temperature sensitivity of microbial respiration remains uncertain (Davidson and Janssens, 2006). An analysis of long-term respiration measurements from the soil around the world suggests that it has increased over the past 2 decades by an amount of 0.1 PgC yr^{-1}, some of which may be due to increased productivity (Bond-Lamberty and Thomson, 2010). If soil respiration were to exceed terrestrial net primary production globally and on a sustained basis, the present net terrestrial sink would become a net source, accelerating the rate of CO_2 build-up in the atmosphere (Luo, 2007).

The carbon stock in freshwater systems is also quite high in global terms. Annual rates of storage (0.03 to 0.07 PgC yr^{-1}) may be trivial compared with sequestration by soils and terrestrial vegetation, but lake sediments are preserved over longer time scales (+10 kyr compared with decades to centuries), and Holocene storage of carbon in lake sediments has been estimated at 820 Pg (Cole et al., 2007). Manmade impoundments represent an increasing and short-lived additional carbon store with conservative annual estimates of 0.16 to 0.2 PgC yr^{-1} (Cole et al., 2007).

A short-duration study of the temperature sensitivity of decomposition in flooded coastal soils, extrapolated to the 21st century, suggested that increases in respiration would exceed increases in future production (Kirwan and Blum, 2011). Further detail on wetland soil carbon stocks can be found in Section 4.3.3.3 on peatlands and on permafrost carbon stocks in Box 4-4 and in Chapter 28.

In summary, biomass and soil carbon stocks in terrestrial ecosystems are currently increasing (*high confidence*) but are vulnerable to loss to the atmosphere as a result of rising temperature, drought, and fire projected in the 21st century (Figure 4-4). Measurements of increased tree growth over the last several decades, a large sink for carbon, are consistent with this but confounding factors such as N deposition, afforestation, and land management make attribution of these trends to climate change difficult (*low confidence*).

4.3.2.4. Evapotranspiration and Water Use Efficiency

Evapotranspiration (ET) includes evaporation from the ground and vegetation surfaces, and transpiration through plant stomata. Both are affected by multiple factors (Luo et al., 2008) including temperature, solar (shortwave) and thermal (longwave) radiation, humidity, soil moisture, and terrestrial water storage; transpiration is additionally affected by CO_2 concentration through its influence on plant stomatal conductance. Studies using lysimeters, evaporation pans, the balance of observed precipitation and runoff, and model reconstructions indicate both increases and decreases in ET in different regions and between approximately 1950 and the present (Huntington, 2008; Teuling et al., 2009; Douville et al., 2013). Flux tower records have at most 15 years duration (FLUXNET, 2012), so there are insufficient data to calculate large-scale, long-term trends. ET can also be estimated from meteorological observations or simulated with models constrained by observations. Estimates of ET from 1120 globally (but non-uniformly) distributed stations indicate that global land mean ET increased by approximately 2.2% between 1982 and 2002, a rate of increase of 0.75 mm yr^{-2} (Wang, K. et al., 2010). Other studies, using data-constrained models, indicated global ET rises of between 0.25 and 1.1 mm yr^{-2} during the 1980s and 1990s (Jung et al., 2010; Vinukollu et al., 2011; Zeng et al., 2012), possibly linked with increased surface solar radiation and thermal radiation (Wild et al., 2008) or warming (Jung et al., 2010). There has been no significant ET trend since approximately 2000 (Jung et al., 2010; Vinukollu et al., 2011; Zeng et al., 2012), possibly due to soil moisture limitation (Jung et al., 2010). Overall, there is *low confidence* in both detection and attribution of long-term trends in ET (Figure 4-4).

Experiments show that rising CO_2 decreases transpiration and increases intrinsic water use efficiency (iWUE, the ratio of photosynthesis to stomatal conductance; Leakey et al., 2009). Some modeling studies suggest that, over the 20th century, the effects of CO_2 on decreasing transpiration are of comparable size but opposite to the effects of rising temperature (Gerten et al., 2008; Peng et al., 2013). However, the observed general increase in ET argues that reduced transpiration cannot be the dominant factor (Huntington, 2008). A meta-analysis of studies at 47 sites across five ecosystem types (Peñuelas et al., 2011) suggests that iWUE for mature trees increased by 20.5% between the 1970s and 2000s. Increased iWUE since preindustrial times (1850 or before) has also been found at several forest sites (Andreu-Hayles et al., 2011; Gagen et al., 2011; Loader et al., 2011; Nock et al., 2011) and also in a temperate semi-natural grassland since 1857 (Koehler et al., 2010), although in one boreal tree species iWUE ceased to increase after 1970 (Gagen et al., 2011).

4.3.2.5. Changes in Species Range, Abundance, and Extinction

Species respond to climate change through genotypic adaptation and phenotypic plasticity; by moving out of unfavorable and into favorable climates; or by going locally or globally extinct (Dawson et al., 2011; Bellard et al., 2012; Peñuelas et al., 2013; see also Section 4.2.3). These responses to climate change can potentially have large impacts on biodiversity and ecosystem services. Genotypic adaptation in the face of strong selection pressure from climate change is typically accompanied

Frequently Asked Questions

FAQ 4.4 | How does climate change contribute to species extinction?

There is a consensus that climate change over the coming century will increase the risk of extinction for many species. When a species becomes extinct, a unique and irreplaceable life form is lost. Even local extinctions can impair the healthy functioning of ecosystems.

Under the fastest rates and largest amounts of projected climate change, many species will be unable to move fast enough to track suitable environments, which will greatly reduce their chances of survival. Under the lowest projected rates and amounts of climate change, and with the assistance of effective conservation actions, the large majority of species will be able to adapt to new climates, or move to places that improve their chances of survival. Loss of habitat and the presence of barriers to species movement increase the risk of extinctions as a result of climate change.

Climate change may have already contributed to the extinction of a small number of species, such as frogs and toads in Central America, but the role of climate change in these recent extinctions is the subject of considerable debate.

by large reductions in abundance (see Section 4.4.1.2). Species range shifts are accompanied by changes in abundance, local extinctions, and colonization that can alter ecosystem services when they affect dominant species such as trees, keystone species such as pollinators, or species that are vectors for diseases (Zarnetske et al., 2012). Global extinctions result in the permanent loss of unique forms of life.

Substantial evidence has accumulated since AR4 reinforcing the conclusion that the geographical ranges of many terrestrial and freshwater plant and animal species have moved over the last several decades in response to warming and that this movement is projected to accelerate over the coming decades under high rates of climate change. Some changes in species abundances appear to be linked to climate change in a predictable manner, with species abundances increasing in areas where climate has become more favorable and vice versa. In contrast, uncertainties concerning attribution to climate change of recent global species extinctions, and in projections of future extinctions, have become more apparent since the AR4.

4.3.2.5.1. Observed species range shifts

The number of studies looking at observed range shifts and the breadth of species examined have greatly increased since AR4. The most important advances since AR4 concern improvements in understanding the relationship between range shifts and changes in climate over the last several decades. The "uphill and poleward" view of species range shifts in response to recent warming (Parmesan and Yohe, 2003; Parmesan, 2006; Fischlin et al., 2007; Chen et al., 2011) is a useful simplification of species responses; however, responses to warming are conditioned by changes in precipitation, land use, species interactions, and many other factors. Investigations of the mechanisms underlying observed range shifts show that climate signals can often be detected, but the impacts of and interactions between changing temperature, precipitation, and land use often result in range shifts that are downhill or away from the poles (Rowe et al., 2010; Crimmins et al., 2011; Hockey et al., 2011; McCain and Colwell, 2011; Rubidge et al., 2011; Pauli et al., 2012; Tingley et al., 2012; Zhu et al., 2012). There are large differences in the ability of species groups (i.e., broad taxonomic categories of species) and species within these groups to track changes in climate through range shifts (Angert et al., 2011; Mattila et al., 2011; Chen et al., 2011). For example, butterflies appear to be able track climate better than birds (community shifts: Devictor et al., 2012; but see Chen et al., 2011 for range shifts) while some plants appear to be lagging far behind climate trends except in mountainous areas (Bertrand et al., 2011; Doxford and Freckleton, 2012; Gottfried et al., 2012; Zhu et al., 2012; Telwala et al., 2013). There is growing evidence that responses at the "trailing edge" of species distributions (i.e., local extinction in areas where climate has become unfavorable) are often less pronounced than responses at the "leading edge" (i.e., colonization of areas where climate has become favorable), which may be related to differences in the rates of local extinction vs. colonization processes (Doak and Morris, 2010; Chen et al., 2011; Brommer et al., 2012; Sunday et al., 2012) and difficulties in detecting local extinction with confidence (Thomas et al., 2006).

Rising water temperatures are also implicated in species range shifts in river fish communities (e.g., Comte and Grenouillet, 2013), combined with a decrease in recruitment and survival as well as range contraction of cold-water species such as salmonids (Bartholow, 2005; Bryant, 2009; Ficke et al., 2007; Jonsson and Jonsson, 2009; Hague et al., 2011). Shifts in freshwater fish species range toward higher elevation and upstream (Hickling et al., 2006; Comte and Grenouillet, 2013) also are not keeping pace with the rate of warming in streams and rivers. While these changes in river temperature regimes may also open up new habitat at higher latitudes (or altitudes) for migratory (Reist et al., 2006) and cool- and warm-water species of fish (Tisseuil et al., 2012), there is *high confidence* that range contraction threatens the long-term persistence of some fully aquatic species.

Rates of recent climate change have varied greatly across the globe, ranging from rapid warming to cooling (Burrows et al., 2011; Dobrowski et al., 2013). Taking this spatial variation into account should enhance the ability to detect climate-related range shifts. A recent synthesis of range shifts indicates that terrestrial animal species have moved at rates that correspond better with changes in temperature when climate is measured only in the regions where the range shifts were observed

(Chen et al., 2011), providing greater confidence in attribution of the range shifts to climate change. Average range shifts across taxa and regions in this study were approximately 17 km poleward and 11 m up in altitude per decade, velocities that are two to three times greater than previous estimates (compare with Parmesan and Yohe, 2003; Fischlin et al., 2007), but these responses differ greatly among species groups. However, this approach remains a simplification, as the climate drivers of species range changes, for example, temperature and precipitation, have frequently shifted in different geographical directions (Dobrowski et al., 2013). Disentangling these conflicting climate signals can help explain complex responses of species ranges to changes in climate (Tingley et al., 2012). Overall, studies since AR4 show that species range changes result from interactions among climate drivers and between climate and non-climate factors. It is the greater understanding of these interactions, combined with increased geographical scope, that leads to *high confidence* that several well-studied species groups, such as insects and birds, have shifted their ranges over significant distances (tens of kilometers or more) over the last several decades, and that these range shifts can be attributed to changes in climate. But for many other species groups range shifts are more difficult to attribute to changes in climate because the climate signal is small, there are many confounding factors, differences between expected and observed range shifts are large, or variability within or between studies is high. Thus there is only *medium confidence* in detection and attribution when examined across all species and all regions.

4.3.2.5.2. Future range shifts

Projections of climate change impacts on future species range shifts since the AR4 have been dominated by studies using Ecological Niche Models (ENMs) that project future ranges based on correlative models of current relationships between environmental factors and species distribution (Peterson et al., 2011). A variety of process-based models are starting to be more widely used to make projections of future species distributions (Buckley et al., 2010; Beale and Lennon, 2012; Cheaib et al., 2012; Higgins et al., 2012; Foden et al., 2013). Model comparisons show that correlative models generally predict larger range shifts than process-based models for trees (Morin and Thuiller, 2009; Kearney et al., 2010; Cheaib et al., 2012). For other species groups that have been studied, differences in projections between model types show no clear tendency (Kearney et al., 2009; Buckley et al., 2010; Bateman et al., 2012). There has been some progress in model validation: projected species shifts are broadly coherent with species responses to climate change in the paleontological record and with observed recent species shifts (see Section 4.2.2 and above in this section), but further validation is needed (Green et al., 2008; Pearman et al., 2008; Nogues-Bravo et al., 2010; Dawson et al., 2011). Modeling studies typically do not account for a number of key mechanisms mediating range shifts, such as genetic adaptation and phenotypic plasticity (see Section 4.4.1.2), species interactions, or human-mediated effects. An important limitation in most studies is that realistic species displacement rates are not accounted for (i.e., rates at which species are able to shift their ranges through dispersal and establishment); as such, they only indicate changes in the location of favorable and unfavorable climates, from which potential shifts in species distribution can be inferred, but not rates of change (Bateman et al., 2013).

Analyses and models developed since AR4 permit the estimation of the ability of a wide range of species to track climate change. Figure 4-5 provides a synthesis of the projected abilities of several species groups to track climate change. This analysis is based on (1) past and future climate velocity, which is a measure of the rate of climate displacement across a landscape and provides an indication of the speed at which an organism would need to move in order to keep pace with the changing climatic conditions (Loarie et al., 2009; Burrows et al., 2011; Chen et al., 2011; Sandel et al., 2011; Feeley and Rehm, 2012; Dobrowski et al., 2013); and (2) species displacement rates across landscapes for a broad range of species (e.g., Stevens, V.M. et al., 2010; Nathan et al., 2011; Barbet-Massin et al., 2012; Kappes and Haase, 2012; Meier et al., 2012; Schloss et al., 2012; see additional references in Figure 4-5 legend). Comparisons of these rates indicate whether species are projected to be able to track climate as it changes. When species displacement capacity exceeds climate velocity it is inferred that species will be able to keep pace with climate change; when displacement capacity is lower than projected climate velocities then they will not, within the bounds of uncertainty of both parameters. This simplified analysis is coherent with more sophisticated model analyses of climate-induced species displacement across landscapes, some of which have evaluated additional constraints such as demographics, habitat fragmentation, or competition (e.g., Meier et al., 2012; Schloss et al., 2012).

Rates of climate change over the 20th century and projected for the 21st century are shown in Figure 4-5a. Rates of climate change for global land surfaces are given for IPCC AR5 climate projections under a wide range of GHG emissions scenarios (i.e., WGI AR5 Chapter 12; Knutti and Sedláček, 2012). Rates of global warming for land surfaces have averaged approximately 0.03°C yr^{-1} since 1980, but have slowed over the last decade and a half (WGI AR5 Chapter 2). At the low end of projected future rates of warming, rates decrease over time, reaching near zero by the end of the century (RCP2.6). At the high end, projected rates increase over time, exceeding 0.06°C yr^{-1} by the end of the century (RCP8.5), and perhaps above 0.08°C yr^{-1} at the upper bound.

Climate velocity is defined as the rate of change in climate over time (e.g., °C yr^{-1}, if only temperature is considered) divided by the rate of change in climate over distance (e.g., °C km^{-1}, if only temperature is considered) and therefore depends on regional rates of climate change and the degree of altitudinal relief (Figure 4-5b; Loarie et al., 2009; Dobrowski et al., 2013). For example, climate velocity for temperature is low in mountainous areas because the change in temperature over short distances is large (e.g., Rocky Mountains, Andes, Alps, Himalayas; Figure 4-5b, leftmost axis). Climate velocity for temperature is generally high in flat areas because the rate of change in temperature over distance is low (e.g., parts of the USA Midwest, Amazon basin, West Africa, central Australia; Figure 4-5b, rightmost axis). In flat areas, climate velocity can exceed 8 km yr^{-1} for the highest rates of projected climate change (RCP8.5). We have focused on climate velocity for temperature change, but several analyses also account for precipitation change.

Rates of displacement vary greatly within and among species groups (Figure 4-5c). Some species groups, notably herbaceous plants and trees, generally have very low displacement capacity. Other species groups such as butterflies, birds (not shown), and large vertebrates generally have a very high capacity to disperse across landscapes, nonetheless

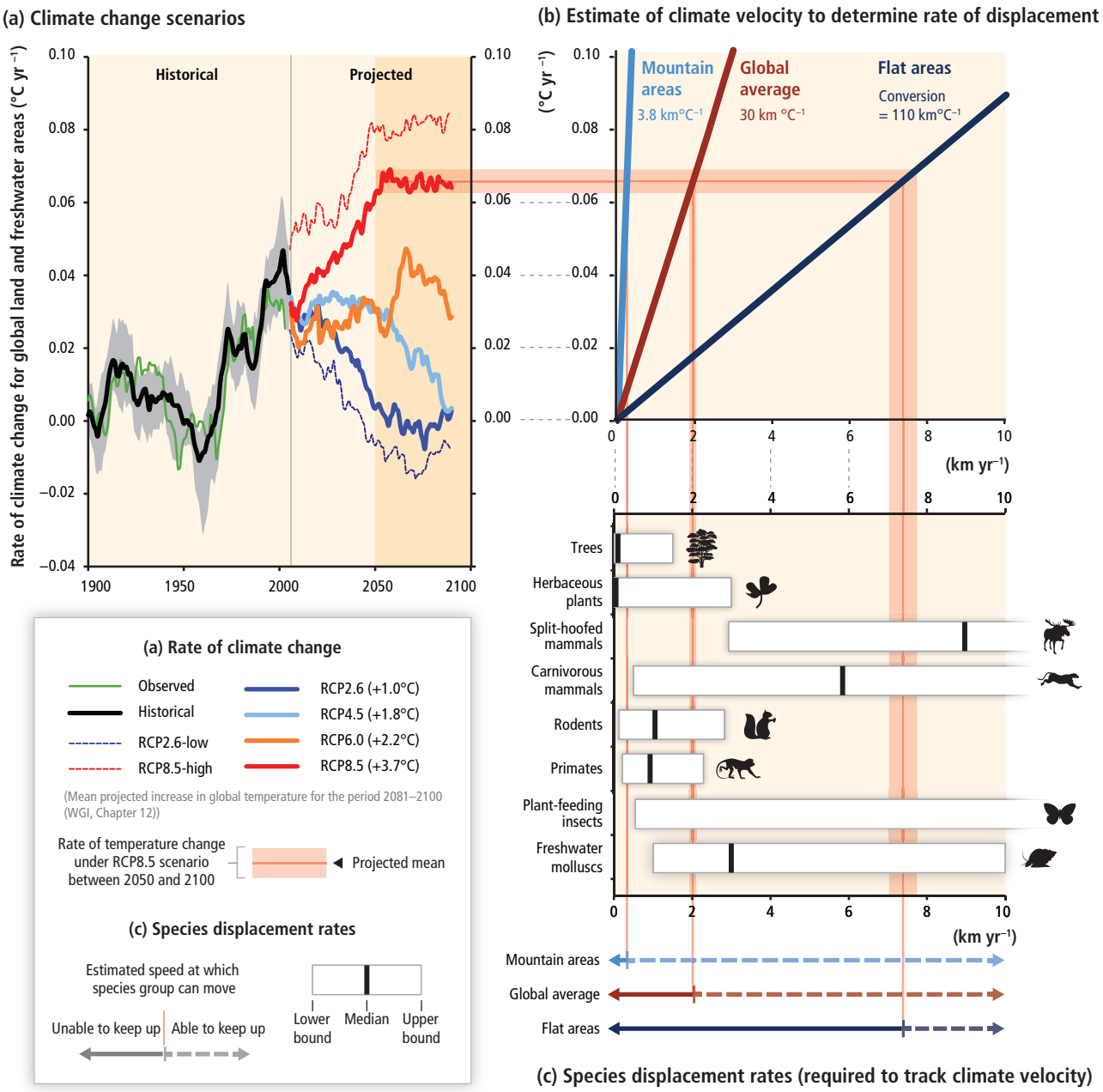


Figure 4-5 | (a) Rates of climate change, (b) corresponding climate velocities, and (c) rates of displacement of several terrestrial and freshwater species groups in the absence of human intervention. Horizontal and vertical pink bands illustrate the interpretation of this figure. Climate velocities for a given range of rates of climate change are determined by tracing a band from the range of rates in (a) to the points of intersection with the three climate velocity scalars in (b). Comparisons with species displacement rates are made by tracing vertical bands from the points of intersection on the climate velocity scalars down to the species displacement rates in (c). Species groups with displacement rates below the band are projected to be unable to track climate in the absence of human intervention. (a) Observed rates of climate change for global land areas are derived from Climatic Research Unit/Hadley Centre gridded land-surface air temperature version 4 (CRUTEM4) climate data reanalysis; all other rates are calculated based on the average of Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model ensembles for the historical period (gray shading indicates model uncertainty) and for the future based on the four Representative Concentration Pathway (RCP) emissions scenarios. Data were smoothed using a 20-year sliding window, and rates are means of between 17 and 30 models using one member per model. Global average temperatures at the end of the 21st century for the four RCP scenarios are from WGI AR5 Chapter 12. (b) Estimates of climate velocity for temperature were synthesized from historical and projected future relationships between rates of temperature change and climate velocity (historical: Burrows et al., 2011; Chen et al., 2011; Dobrowski et al., 2013; projected future: Loarie et al., 2009; Sandel et al., 2011; Feeley and Rehm, 2012). The three scalars are climate velocities that are representative of mountainous areas (left), averaged across global land areas (center), and large flat regions (right). (c) Rates of displacement are given with an estimate of the median (black bars) and range (boxes = approximately 95% of observations or models for herbaceous plants, trees, and plant-feeding insects or median ± 1.5 inter-quartile range for mammals). Displacement rates for herbaceous plants were derived from paleobotanical records, modern plant invasion rates, and genetic analyses (Kinlan and Gaines, 2003). Displacement estimates for trees are based on reconstructed rates of tree migration during the Holocene (Clark, 1998; Clark et al., 2003; Kinlan and Gaines, 2003; McLachlan et al., 2005; Nathan, 2006; Pearson, 2006) and modeled tree dispersal and establishment in response to future climate change (Higgins et al., 2003; Iverson et al., 2004; Epstein et al., 2007; Goetz et al., 2011; Nathan et al., 2011; Meier et al., 2012; Sato and Ise, 2012). Displacement rates for mammals were based on modeled dispersal rates of a wide range of mammal species (mean of Schloss et al., 2012 for Western Hemisphere mammals and rates calculated from global assessments of dispersal distance by Santini et al., 2013 and generation length by Pacifici et al., 2013). Displacement rates for phytophagous insects are based on observed dispersal distances and genetic analyses (Peterson and Denno, 1998; Kinlan and Gaines, 2003; Schneider, 2003; Berg et al., 2010; Chen et al., 2011). The estimate of median displacement rate for this group exceeds the highest rates on the axis. These displacement rates do not take into account limitations imposed by host plants. Displacement estimates for freshwater molluscs correspond to the range of passive plus active dispersal rates for upstream movement (Kappes and Haase, 2012).

some species in these groups have low dispersal capacity. Current and future rates of climate change correspond to climate velocities that exceed rates of displacement for several species groups for most climate change scenarios. This is particularly true for mid- and late-successional trees that have maximum displacement rates that are on the order of tens to a few hundreds of meters per year. Overall, many plant species are foreseen to be able to track climates only in mountainous areas at medium to high rates of warming, though there is uncertainty concerning the potential role of long-distance dispersal (Pearson, 2006). Primates generally have substantially higher dispersal capacity than trees; however, a large fraction of primates are found in regions with very high climate velocities, in particular the Amazon basin, thereby putting them at high risk of being unable to track climates even at relatively low rates of climate change (Schloss et al., 2012). On a global average, many rodents, as well as some carnivores and freshwater molluscs, are projected to be unable to track climate at very high rates of climate change (i.e., >0.06°C yr^{-1}). These projected differences in species ability to keep pace with future climate change are broadly coherent with observations of species ability or inability to track recent global warming (see Section 4.3.2.5.1).

Humans can increase species displacement rates by intentionally or unintentionally dispersing individuals or propagules. For example, many economically important tree species may be deliberately moved on large scales as part of climate adaptation strategies in forestry in some regions (Lindner et al., 2010). Human activities can also substantially reduce displacement rates. In particular, habitat loss and fragmentation typically reduces displacement rates, sometimes substantially (Eycott et al., 2012; Hodgson et al., 2012; Meier et al., 2012; Schloss et al., 2012). The degree to which habitat fragmentation slows displacement depends on many factors, including the spatial pattern of the fragments and corridors, maximum dispersal distances, population dynamics, and the suitability of intervening modified habitats as stepping-stones (Pearson and Dawson, 2003). Species and habitat dependencies may also speed or hinder species displacement. For example, host plants are projected to move much more slowly than most herbivorous insects, substantially slowing displacement of the insects if they are unable to switch host plants (Schweiger et al., 2012). Likewise, many habitats are structured by slow moving plants, so habitat shifts are projected to lag behind climate change (Hickler et al., 2012; Jones et al., 2012), which will in turn mediate the movements of habitat specialists.

There are significant uncertainties in climate velocities, measured estimates of dispersal and establishment rates, and model formulations. Climate velocities are calculated using a variety of methods and spatial resolutions, making direct comparisons difficult and leading to *low confidence* in estimates of climate velocities in Figure 4-5b (*limited evidence* and *medium agreement*). The lowest estimates of global average climate velocity (Figure 4-5b, center axis) are about half the best estimate values we show on the climate velocity axes (Loarie et al., 2009), while the highest estimates are about four times higher (Burrows et al., 2011), but high estimates may be artefacts of using very large spatial resolutions (Dobrowski et al., 2013). In addition, the climate velocities used in Figure 4-5 are based on temperature alone, and recent analyses indicate that including more climate factors increases climate velocity (Feeley and Rehm, 2012; Dobrowski et al., 2013). Species displacement rates are calculated based on a very wide range of methods including rates of displacement in the paleontological record, rates of current range shifts due to climate warming, models of dispersal and establishment, maximum observed dispersal distances and genetic analyses (e.g., Kinlan and Gaines, 2003; Stevens, V.M. et al., 2010). There are often large differences in estimates of dispersal rates across methods due to intrinsic uncertainties in the methods and differences in the mechanisms included (Kinlan and Gaines, 2003; Stevens, V.M. et al., 2010). For example, estimates of tree displacement rates are frequently based on models or observations that explicitly or implicitly include both dispersal of seeds and biotic and abiotic factors controlling establishment of adult trees. Displacement rates of trees are often more strongly limited by establishment than dispersal (Higgins et al., 2003; Meier et al., 2012). It is reasonable to expect that limits on establishment could also be important for other species groups, but often only dispersal rates have been calculated, leading to an overestimation of displacement rates. For trees there is *medium confidence* in projections of their displacement rates due to the large number of studies of past, current, and future displacement rates (*robust evidence* and *medium agreement*). Less is known for other broad species groups such as mammals, so there is only *low confidence* in estimates of their displacement capacity. Estimates for other groups, such as freshwater molluscs, are based on very little data, so estimates of their dispersal capacity are poorly constrained.

Despite large uncertainties in displacement capacity and climate velocity, the rates of displacement required to track the highest rates of climate change (RCP8.5) are so high that many species will be unable to do so (*high confidence*). Moderate rates of projected climate change (RCP4.5 and RCP6.0) would allow more species to track climate, but would still exceed the capacity of many species to track climate (*medium confidence*). The lowest rates of projected climate change (RCP2.6) would allow most species to track climate toward the end of the century (*high confidence*). This analysis highlights the importance of rates of climate change as an important component of climate change impacts on species and ecosystems. For example, differences in the magnitude of climate change between scenarios are small at mid-21st century (WGI AR5 Chapter 12), but the differences in rates of climate change are large. At mid-century, it is projected that species would need to move little at the lowest rates of climate change (RCP2.6), but will need to move approximately 70 km per decade in flat areas in order to track climate at the highest rates of climate change (RCP8.5).

Species that cannot move fast enough to keep pace with the rate of climate change will lose favorable climate space and experience large range contractions (Warren et al., 2013), whereas displacement that keeps pace with climate change greatly increases the fraction of species that can maintain or increase their range size (Menéndez et al., 2008; Pateman et al., 2012). Mountains provide an extremely important climate refuge for many species because the rate of displacement required to track climate is low (Figure 4-5b; Colwell et al., 2008; Engler et al., 2011; Gottfried et al., 2012; Pauli et al., 2012; but see Dullinger et al., 2012). However, species that already occur near mountaintops (or other boundaries) are among the most threatened by climate change because they cannot move upwards (Ponniah and Hughes, 2004; Thuiller et al., 2005; Raxworthy et al., 2008; Engler et al., 2011; Sauer et al., 2011). The consequences of losing favorable climate space are not yet well understood. The extent to which adaptive responses might allow persistence in areas of unfavorable climates is discussed in Section

4.4.1.2. In the absence of adaptation, losing favorable climate space is projected to lead to reduced fitness, declining abundance, and local extinction, with potentially large effects on biodiversity and ecosystem services (see evidence of early signs of this for trees in Box 4-2).

4.3.2.5.3. Observed changes in abundance and local extinctions

Observations of range shifts imply changes in abundance, that is, colonization at the "leading edge" and local extinction at the "trailing edge" of ranges. Evidence that the attribution of these responses to recent changes in climate can be made with *high confidence* for several species groups is reviewed here (Section 4.3.2.5), in AR4, and by Cahill et al. (2013). Changes in abundance, as measured by changes in the population size of individual species or shifts in community structure within existing range limits, have also occurred in response to recent global warming (*high confidence*; Thaxter et al., 2010; Bertrand et al., 2011; Naito and Cairns, 2011; Rubidge et al., 2011; Devictor et al., 2012; Tingley et al., 2012; Vadadi-Fulop et al., 2012; Cahill et al., 2013; Ruiz-Labourdette et al., 2013). Confident attribution to recent global warming is hindered by confounding factors such as disease, land use change, and invasive species (Cahill et al., 2013). New tentative conclusions since AR4 are that climate-related changes in abundance and local extinctions appear to be more strongly related to species interactions than to physiological tolerance limits (*low confidence*; Cahill et al., 2013) and that precipitation can be a stronger driver of abundance change than temperature in many cases (Tian et al., 2011; Tingley et al., 2012). This gives weight to concerns that biological interactions, which are poorly known and modeled, may play a critical role in mediating the impacts of future climate change on species abundance and local extinctions (Dunn et al., 2009; Bellard et al., 2012; Hannah, 2012; Urban et al., 2012; Vadadi-Fulop et al., 2012).

A few examples illustrate the types of change in abundance that are being observed and the challenges in attributing these to recent global warming. Some of the clearest examples of climate-related changes in species populations come from high-latitude ecosystems where non-climate drivers are of lesser importance. For example, both satellite data and a large number of long-term observations indicate that shrub abundance is generally increasing over broad areas of Arctic tundra, which is coherent with predicted shifts in community structure due to warming (Epstein et al., 2007; Goetz et al., 2011; Myers-Smith et al., 2011). In the Antarctic, two native vascular plants, Antarctic pearlwort (*Colobanthus quitensis*) and Antarctic hair grass (*Deschampsia antarctica*), have become more prolific over recent decades, perhaps because they benefit more from warming of soils than do mosses (Hill et al., 2011). Penguin populations have declined in several areas of the Antarctic, including a recent local extinction of an Emperor penguin (*Aptenodytes forsteri*) population that has been attributed to regional changes in climate (Trathan et al., 2011). The attribution of these declines to changes in regional climate is well supported, but the link to global warming is tenuous (Barbraud et al., 2011).

Mountains also provide good examples of changes in abundance that can be linked to climate because very strong climate gradients are found there. AR4 highlighted these responses, and the case for changes in abundance, in particular plants, has become stronger since then. For example, Pauli et al. (2012) reported an increase in species richness from plant communities of mountaintops in the European boreal and temperate zones due to increasing temperatures and a decrease in species richness on the Mediterranean mountain tops, probably due to a decrease in the water availability in southern Europe. An increase in the population size of warm-adapted species at high altitudes also appears to be attributable to increasing temperatures (Gottfried et al., 2012). However, these attributions are complicated by other anthropogenic influences such as changes in grazing pressure, atmospheric N deposition, and forest management practices (Gottfried et al., 2012). Altitudinal gradients in local and global extinctions of amphibians also contributed to the attribution of these extinctions to recent global warming, although this attribution remains controversial (see Section 4.3.2.5.5).

4.3.2.5.4. Projected changes in abundance and local extinction

Ecological niche models do not predict population changes, but the shifts in suitable climates can be used to infer areas where species populations might decline or increase. These models project that local extinction risk by the end of the 21st century due to climate change will vary widely, ranging from almost no increase in local extinction risk within the current range for some species or species groups to greatly increased risk of local extinctions in more than 95% of the present-day range for others (Settele et al., 2008; Bellard et al., 2012). Projected local colonization rates are equally variable. There has been progress in coupling species distribution models and species abundance models for a wide range of organisms (Keith et al., 2008; Midgley et al., 2010; Matthews et al., 2011; Schippers et al., 2011; Oliver et al., 2012a; Renwick et al., 2012). These hybrid approaches predict extinction risk directly, rather than by inference from changes in climate suitability (Fordham et al., 2012). The main conclusions from these studies are that changes in species abundance and local extinction risk as a result of climate change can range from highly positive to highly negative, and are determined by a combination of factors, including its environmental niche, demographics, and life history traits, as well as interactions among these factors (Aiello-Lammens et al., 2011; Clavero et al., 2011; Conlisk et al., 2012; Fordham et al., 2012; Swab et al., 2012).

Changes in abundances will also be accompanied by changes in genetic diversity (see also Section 4.4.1.2). At the intraspecific level, future climate change is projected to induce losses of genetic diversity when it results in range contraction (Balint et al., 2011; Pauls et al., 2013). In addition, there is theoretical and observational evidence this loss of genetic diversity will depend on rates of migration and range contraction (Arenas et al., 2012). In these cases, reductions in genetic diversity may then decrease the ability of species to adapt to further climate change or other global changes. Climate change may also compound losses of genetic diversity that are already occurring due to other global changes such as the introduction of alien species or habitat fragmentation (Winter et al., 2009; see also Section 4.2.4.6).

4.3.2.5.5. Observed global extinctions

Global species extinctions, many of them caused by human activities, are now occurring at rates that approach or exceed the upper limits of

observed natural rates of extinction in the fossil record (Barnosky et al., 2011). However, across all taxa there is only *low confidence* that rates of species extinctions have increased over the last several decades (birds: Szabo et al., 2012; but see Kiesecker, 2011, for amphibians). Most extinctions over the last several centuries have been attributed to habitat loss, overexploitation, pollution, or invasive species, and these are the most important current drivers of extinctions (Millennium Ecosystem Assessment, 2005b; Hofmann and Todgham, 2010; Cahill et al., 2013). Of the more than 800 global extinctions documented by the International Union for Conservation of Nature (IUCN), only 20 have been tenuously linked to recent climate change (Cahill et al., 2013; see also Hoffmann et al., 2010; Szabo et al., 2012). Molluscs, especially freshwater molluscs, have by far the highest rate of documented extinctions of all species groups (Barnosky et al., 2011). Mollusc extinctions are attributed primarily to invasive species, habitat modification, and pollution; changes in climate are rarely evoked as a driver (Lydeard et al., 2004; Regnier et al., 2009; Chiba and Roy, 2011; but see a few cases in Kappes and Haase, 2012; Cahill et al., 2013). Freshwater fish have the highest documented extinction rates of all vertebrates, and again very few have been attributed to changing climate, even tenuously (Burkhead, 2012; Cahill et al., 2013). In contrast, changes in climate have been identified as one of the key drivers of extinctions of amphibians (Pounds et al., 2006). There have been more than 160 probable extinctions of amphibians documented over the last 2 decades, many of them in Central America (Pounds et al., 2006; Kiesecker, 2011). The most notable cases have been the golden toad (*Bufo periglenes*) and Monteverde harlequin frog (*Atelopus varius*) of Central America, which belong to a group of amphibians with high rates of extinction previously ascribed to global warming with "very high confidence" (Pounds et al., 2006; Fischlin et al., 2007). This case has raised a number of important issues about attribution because (1) the proximate causes of extinction of these and other Central American frogs appear to be an extremely virulent invasive fungal infection and land use change, with regional changes in climate as a potential contributing factor, and (2) changes in regional climate may have been related to natural climate fluctuations rather than anthropogenic climate change (Sodhi et al., 2008; Lips et al., 2008; Anchukaitis and Evans, 2010; Bustamante et al., 2010; Collins, 2010; Vredenburg et al., 2010; Kiesecker, 2011; McKenzie and Peterson, 2012; McMenamin and Hannah, 2012). Owing to *low agreement* among studies there is only *medium confidence* in detection of extinctions and attribution of Central American amphibian extinctions to climate change. While this case highlights difficulties in attribution of extinctions to recent global warming, it also points to a growing consensus that it is the interaction of climate change with other global change pressures that poses the greatest threat to species (Brook et al., 2008; Pereira et al., 2010; Hof et al., 2011b). Overall, there is *very low confidence* that observed species extinctions can be attributed to recent climate warming, owing to the very low fraction of global extinctions that have been ascribed to climate change and tenuous nature of most attributions.

4.3.2.5.6 Projected future species extinctions

Projections of future extinctions due to climate change have received considerable attention since AR4. AR4 stated with *medium confidence* "that approximately 20–30% of the plant and animal species assessed to date are at increasing risk of extinction as global mean temperatures exceed a warming of 2-3°C above preindustrial levels" (Fischlin et al., 2007). All model-based analyses since AR4 broadly confirm this concern, leading to *high confidence* that climate change will contribute to increased extinction risk for terrestrial and freshwater species over the coming century (Pereira et al., 2010; Sinervo et al., 2010; Pearson, 2011; Warren et al., 2011, 2012; Bellard et al., 2012; Hannah, 2012; Ihlow et al., 2012; Sekercioglu et al., 2012; Wearn et al., 2012; Foden et al., 2013). Most studies indicate that extinction risk rises rapidly with increasing levels of climate change, but some do not (Pereira et al., 2010). The limited number of studies that have directly compared land use and climate change drivers have concluded that projected land use change will continue to be a more important driver of extinction risk throughout the 21st century (Pereira et al., 2010). There is, however, broad agreement that land use, and habitat fragmentation in particular, will pose serious impediments to species adaptation to climate change as it is projected to reduce the capacity of many species to track climate (see Section 4.3.2.5.3). These considerations lead to the assessment that future species extinctions are a high risk because the consequences of climate change are potentially severe, widespread, and irreversible, as extinctions constitute the permanent loss of unique life forms.

There is, however, low agreement concerning the overall fraction of species at risk, the taxa and places most at risk, and the time scale for climate change-driven extinctions to occur. Part of this uncertainty arises from differences in extinction risks within and between modeling studies: this uncertainty has been evaluated in AR4 and subsequent syntheses (Pereira et al., 2010; Warren et al., 2011; Bellard et al., 2012; Cameron, 2012). All studies project increased extinction risk by the end of the 21st century due to climate change, but as indicated in AR4 the range of estimates is large. Recent syntheses indicate that model-based estimates of the fraction of species at substantially increased risk of extinction due to 21st century climate change range from below 1% to above 50% of species in the groups that have been studied (Pereira et al., 2010; Bellard et al., 2012; Cameron, 2012; Foden et al., 2013). Differences in modeling methods, species groups, and climate scenarios between studies make comparisons between estimates difficult (Pereira et al., 2010; Warren et al., 2011; Cameron, 2012).

Many papers published since AR4 argue that the uncertainty may be even higher than indicated in syntheses of model projections, due to limitations in the ability of current models to evaluate extinction risk (e.g., Kuussaari et al., 2009; Pereira et al., 2010; Dawson et al., 2011; McMahon et al., 2011; Pearson, 2011; Araujo and Peterson, 2012; Bellard et al., 2012; Fordham et al., 2012; Hannah, 2012; Kramer et al., 2012; Zurell et al., 2012; Halley et al., 2013; Moritz and Agudo, 2013). Models frequently do not account for genetic and phenotypic adaptive capacity, dispersal capacity, population dynamics, the effects of habitat fragmentation and loss, community interactions, micro-refugia, and the effects of rising CO_2 concentrations, all of which could play a major role in determining species vulnerability to climate change, causing models to either over- or underestimate risk. In addition, difficulties in model validation, large variation in the climate sensitivity of species groups, and uncertainties about time scales linking extinction risks to range reductions also lead to large uncertainty in model-based estimates of extinction risk.

A variety of studies since AR4 illustrate how accounting for these factors alters estimates of extinction risk. Accounting for biotic interactions

such as pollination or predator-prey networks can increase modeled extinction risks, at least for certain areas and species groups (Schweiger et al., 2008; Urban et al., 2008; Hannah, 2012; Nakazawa and Doi, 2012), or can decrease extinction risk (Menéndez et al., 2008; Pateman et al., 2012). Accounting for climatic variation at fine spatial scales may increase (Randin et al., 2009; Gillingham et al., 2012; Suggitt et al., 2012; Dobrowski et al., 2013; Franklin et al., 2013) or decrease (Trivedi et al., 2008; Engler et al., 2011; Shimazaki et al., 2012) the persistence of small populations under future climate change. Several recent studies indicate that correlative species distribution models (the type of model most frequently used for evaluating species extinction risk) tend to be much more pessimistic concerning plant species range contractions and the inferred extinction risks due to climate change when compared to mechanistic models that explicitly account for the interactions between climate change and protective effects of rising CO_2 concentrations on plants (Morin and Thuiller, 2009; Kearney et al., 2010; Cheaib et al., 2012). Models that account for population dynamics indicate that some species populations, such as those of polar bears (Hunter et al., 2010), will decline precipitously over the course of the next century due to climate change, greatly increasing extinction risk, while others may not (Keith et al., 2008). Phenotypic plasticity in one very well-studied temperate bird population has been estimated to be sufficient to keep extinction risk low even with projected warming exceeding 2–3°C (Vedder et al., 2013), but this and other studies suggest that capacity for adaptation is often substantially lower in species with long generation times (see Section 4.4.1.2). There is evidence that interactions between physiological tolerances and regional climate change will lead to large taxonomic and spatial variation in extinction risk (Deutsch et al., 2008; Sinervo et al., 2010). Even species whose populations are not projected to decline rapidly over the next century can face a substantial "extinction debt," that is, will be in unfavorable climates that over a period of many centuries are projected to lead to large reductions in population size and increase the risk of extinction (Dullinger et al., 2012). Finally, evidence from the paleontological record indicating very low extinction rates over the last several hundred thousand years of substantial natural fluctuations in climate—with a few notable exceptions such as large land animal extinctions during the Holocene—has led to concern that forecasts of very high extinction rates due entirely to climate change may be overestimated (Botkin et al., 2007; Dawson et al., 2011; Hof et al., 2011a; Willis and MacDonald, 2011; Moritz and Agudo, 2013). However, as indicated in Section 4.2.3, no past climate changes are precise analogs of future climate change in terms of speed, magnitude, and spatial scale; nor did they occur alongside the habitat modification, overexploitation, pollution, and invasive species that are characteristic of the 21st century. Therefore the paleontological record cannot easily be used to assess future extinction risk due to climate change.

4.3.3. Impacts on and Risks for Major Systems

This section covers impacts of climate change on broad categories of terrestrial and freshwater ecosystems of the world. We have placed a particular emphasis on those ecosystems that have high exposure to climate change or that may be pushed past thresholds or "tipping points" by climate change. Two geographical regions of particularly high risk have been identified in recent studies: (1) tropics, due to the limited capacity of species to adapt to moderate global warming and (2) high northern latitude systems, because temperature increases are projected to be large. There has been a tendency to oppose these two points of view, but there is a high risk in both types of systems, albeit for different reasons (Corlett, 2011). Tropical species, which experienced low inter- and intra-annual climate variability, have evolved within narrow thermal limits, and are already near their upper thermal limits (ectotherms: Deutsch et al., 2008; Huey et al., 2012; birds: Sekercioglu et al., 2012; trees: Corlett, 2011). On this basis, tropical species and ecosystems are predicted to be more sensitive to climate change than species and ecosystems that have evolutionary histories of climatic variability (e.g., Arctic and boreal ecosystems; Beaumont et al., 2011). However, there are physiological, evolutionary, and ecological arguments that tropical species and ecosystem sensitivities to climate change are complex and may not be particularly high compared to other systems (Gonzalez et al., 2010; Corlett, 2011; Laurance et al., 2011; Gunderson and Leal, 2012; Walters et al., 2012). High-latitude systems have the greatest projected exposure to rising temperatures (WGI AR5 Chapter 12; Diffenbaugh and Giorgi, 2012), which all else being equal would put them at higher risk. The greatest degree of recent climate warming has occurred at high northern latitudes (Burrows et al., 2011) and the strongest and clearest signals of recent climate warming impacts on ecosystems come from these regions. A comparison of modeled biome level vulnerability indicated that temperate and high northern latitude systems are also the most vulnerable in the future (Gonzalez et al., 2010).

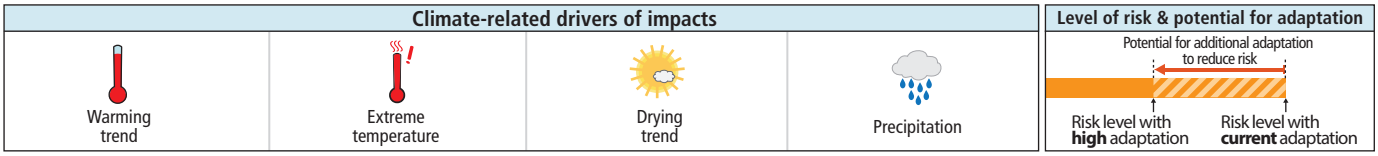
Several potential tipping points (see Section 4.2.1) with regional and global consequences have been identified (Scheffer, 2009); two are elaborated in Boxes 4-3 (Amazon dieback) and 4-4 (tundra-boreal regime shift). An assessment by the authors of this chapter of the top risks in relation to climate change and terrestrial and freshwater ecosystems is presented in Table 4-3.

4.3.3.1. Forests and Woodlands

Forests and woodlands are principal providers of timber, pulp, bioenergy, water, food, medicines, and recreation opportunities and can play prominent roles in cultural traditions. Forests are the habitat of a large fraction of the Earth's terrestrial plant and animal species, with the highest concentrations and levels of endemism found in tropical regions (Gibson et al., 2011). Climate change and forests interact strongly; air temperature, solar radiation, rainfall, and atmospheric CO_2 concentrations are major drivers of forest productivity and forest dynamics, and forests help control climate through the large amounts of carbon they can remove from the atmosphere or release, through absorption or reflection of solar radiation (albedo), cooling through evapotranspiration, and the production of cloud-forming aerosols (Arneth et al., 2010; Pan et al., 2011; Pielke et al., 2011).

Combinations of ground-based observations, atmospheric carbon budgets, and satellite measurements indicate with *high confidence* that forests are currently a net sink for carbon at the global scale. It is estimated that intact and regrowing forests currently contain 860 ± 70 PgC and sequestered 4.0 ± 0.7 PgC yr^{-1} globally between 2000 and 2007 (WGI AR5 Chapter 6; Canadell et al., 2007; Pan et al., 2011; Le Quéré et al., 2012). The carbon taken up by intact and regrowing forests was counterbalanced by a release due to land use change of 2.8 ± 0.4

Table 4-3 | Key risks for terrestrial and freshwater ecosystems from climate change and the potential for reducing risk through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments by chapter authors, with evaluation of evidence and agreement in supporting chapter sections. Each key risk is characterized as very low to very high. Risk levels are presented in three time frames: the present, near term (here, assessed over 2030–2040), and longer term (here, assessed over 2080–2100). For the near term era of committed climate change, projected levels of global mean temperature increase do not diverge substantially across emission scenarios. For the longer term era of climate options, risk levels are presented for global mean temperature increase of 2°C and 4°C above pre-industrial levels. For each timeframe, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adapted state. Relevant climate variables are indicated by icons. For a given key risk, change in risk level through time and across magnitudes of climate change is illustrated, but because the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks, sectors, or regions.



Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Reduction in terrestrial carbon sink: Carbon stored in terrestrial ecosystems is vulnerable to loss back into the atmosphere. Key mechanisms include an increase in fire frequency due to climate change and the sensitivity of ecosystem respiration to rising temperatures. (*medium confidence*) [4.2.4, 4.3.2, 4.3.3]	Adaptation prospects include managing land use (including deforestation), fire, and other disturbances and non-climatic stressors.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Boreal tipping point: Arctic ecosystems are vulnerable to abrupt change related to the thawing of permafrost and spread of shrubs in tundra and increase in pests and fires in boreal forests. (*medium confidence*) [4.3.3.1.1, Box 4-4]	There are few adaptation options in the Arctic.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Amazon tipping point: Moist Amazon forests could change abruptly to less carbon-dense drought and fire-adapted ecosystems. (*low confidence*) [4.3.3.1.3, Box 4-3]	Policy and market measures to reduce deforestation and fire.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Tree mortality and forest loss: Tree mortality has been observed to have increased in many places and has been attributed in some cases to direct climate effects and indirect effects due to pests and diseases. The dead trees increase the risk of forest fires. (*medium confidence*) [4.3.3.1, Box 4-2]	Adaption options include more effective management of fire, pests, and pathogens.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Increased risk of species extinction: A large fraction of the species that have been assessed are vulnerable to extinction as a result of climate change, often in interaction with other threats. Species with an intrinsically low dispersal rate, especially when occupying flat landscapes where the projected climate velocity is high, and species in isolated habitats such as mountain tops, islands, or small protected areas are especially at risk. Cascading effects through organism interactions, and especially those vulnerable to timing (phenological) changes, amplify the risk. (*high confidence*) [4.3.2.5, 4.3.3.3, 4.3.2.1, 4.4.2]	Adaptation options include reducing habitat modification, habitat fragmentation, pollution, over-exploitation, and invasive species; protected area expansion, assisted dispersal, *ex situ* conservation.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Invasion by non-native species: Disruptions of species interactions and the increase in physiological stress as a result of being near the edge or outside of the historical climate niche increases the vulnerability of ecosystems to invasion by non-native (alien) species, especially in the presence of increased long-distance dispersal opportunities. In the extreme this can result in biome shifts, with consequent changes in the spectrum of ecosystem services provided. (*high confidence*) [4.2.4.6]	Climate is one driver among many. Adaptation options are limited, largely based on reducing other stresses and measures to slow the unintended arrival of aliens. Intensive direct intervention in controlling emergent invasive species is an option, but could be overwhelmed by the rapidly rising number of cases.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high

PgC yr^{-1} over this same period due mostly to tropical deforestation and forest degradation associated with logging and fire, resulting in a net carbon balance for global forests of 1.1±0.8 PgC yr^{-1}.

The future of the interaction between climate and forests is unclear. The carbon taken up by intact and regrowing forests appears to have stabilized compared to the 1990s, after having increased in the 1970s and 1980s (Canadell et al., 2007; Pan et al., 2011). There is *medium confidence* that the terrestrial carbon sink is weakening. The drivers behind the forest carbon sink vary greatly across regions. They include forest regrowth and stimulation of carbon sequestration by climate change, rising atmospheric CO_2 concentrations, and nitrogen deposition

(Pan et al., 2011; see also Sections 4.2.4.1, 4.2.4.2, 4.2.4.4). Most models suggest that rising temperatures, drought, and fires will lead to forests becoming a weaker sink or a net carbon source before the end of the century (Sitch et al., 2008; Bowman et al., 2009). Fires play a dominant role in driving forest dynamics in many parts of the world; forest susceptibility to fire is projected to change little for the lowest emissions scenario (RCP2.6), but substantially for the high emissions scenario (RCP8.5; Figure 4-6). There is *low agreement* on whether climate change will cause fires to become more or less frequent in individual locations (Figure 4-6). Climate change-mediated disease and insect outbreaks could exacerbate climate-driven increases in fire susceptibility (Kurz et al., 2008). The greatest risks for large positive feedbacks from forests to climate through changes in disturbance regimes arise from widespread tree mortality and fire in tropical forests and low-latitude areas of boreal forests, as well as northward expansion of boreal forests into Arctic tundra (Lenton et al., 2008; Kriegler et al., 2009; Good et al., 2011b).

Recent evidence suggests (*low confidence*) that the stimulatory effects of global warming and rising CO_2 concentrations on tree growth may have already peaked in many regions (Charru et al., 2010; Silva et al., 2010; Silva and Anand, 2013) and that warming and changes in precipitation are increasing tree mortality in a wide range of forest systems, acting via heat stress, drought stress, pest outbreaks, and a wide range of other indirect impact mechanisms (Allen, C.D. et al., 2010; Box 4-2). Detection of a coherent global signal is hindered by the lack of long-term observations in many regions and attribution to climate change is difficult because of the multiplicity of mechanisms mediating mortality (Allen, C.D. et al., 2010).

Deforestation has slowed over the last decade (Meyfroidt and Lambin, 2011). This includes substantial reductions in tropical deforestation in some regions, such as the Brazilian Amazon, where deforestation rates declined rapidly after peaking in 2005 (Nepstad et al., 2009; INPE, 2013). Growing pressure for new crop (Section 4.4.4) and grazing land will continue to drive tropical deforestation (*medium confidence*), although recent policy experiments and market-based interventions in land use demonstrate the potential to reduce deforestation (Meyfroidt and Lambin, 2011; Westley et al., 2011; Nepstad et al., 2013).

4.3.3.1.1. Boreal forests

Most projections suggest a poleward expansion of forests into tundra regions, accompanied by a general shift in composition toward more temperate plant functional types (e.g., evergreen needleleaf being replaced by deciduous broadleaf; or in colder regions, deciduous needleleaf replaced by evergreen needleleaf (Lloyd et al., 2011; Pearson et al., 2013). Projections of climate-driven changes in boreal forests over the next few centuries remain uncertain on some issues, partly as a result of different processes of change being considered in different models. In particular, the inclusion or exclusion of fire and insects makes a big difference, possibly making the boreal forest more susceptible to a rapid, nonlinear, or abrupt decline in some regions (Bernhardt et al., 2011; Mann et al., 2012; Scheffer et al., 2012; see WGI AR5 Chapter 12). Recent observed change (Box 4-2) and dynamic vegetation modeling (e.g., Sitch et al., 2008) suggest that regions of the boreal forest could experience widespread forest dieback, although there is *low confidence* owing to conflicting results (Sitch et al., 2008; Gonzalez et al, 2010) and poor understanding of relevant mechanisms (WGI AR5 Section 12.5.5.6). If such shifts were to occur, they would put the boreal carbon sink at risk (Pan et al., 2011; Mann et al., 2012).

Whereas boreal forest productivity has been expected to increase as a result of warming (Hari and Kulmata, 2008; Bronson et al., 2009; Zhao and Running, 2010; Van Herk et al., 2011), and early analyses of satellite observations confirmed this trend in the 1980s (*medium confidence*), more recent and longer-term assessments indicate with *high confidence* that many areas of boreal forest have instead experienced productivity declines (*high confidence*; Goetz et al., 2007; Parent and Verbyla, 2010; Beck, P.S.A. et al., 2011; de Jong et al., 2011). The best evidence to date indicates that these "browning trends" are due to warming-induced drought, specifically the greater drying power of air (vapor pressure deficit; Williams et al., 2013), inducing photosynthetic down-regulation of boreal tree species, particularly conifer species, most of which are not adapted to the warmer conditions (Welp et al., 2007; Bonan, 2008; Van Herk et al., 2011). Satellite evidence for warming-induced productivity declines has been corroborated by tree ring studies (Barber et al., 2000; Hogg et al., 2008; Beck, P.S.A. et al., 2011; Porter and Pisaric, 2011; Griesbauer and Green, 2012) and long-term tree demography plots in more continental and densely forested areas (Peng et al., 2011; Ma et al., 2012). Conversely, productivity has increased at the boreal-tundra ecotone, where more mesic (moist) conditions may be generating the expected warming-induced positive growth response (Rupp et al., 2001; McGuire et al., 2007; Goldblum and Rigg, 2010; Beck, P.S.A. et al., 2011). The complexity of boreal forest response also involves tree age and size, with younger trees and stands perhaps being more able to benefit from warming where other factors are not limiting (Girardin et al., 2011, 2012).

Where they occur, warming and drying, coupled with productivity declines, insect disturbance, and associated tree mortality, also favor greater fire disturbance (*high confidence*). The boreal biome fire regime has intensified regionally in recent decades, exemplified by increases in the extent of area burned but also a longer fire season and more episodic fires that burn with greater energy output or intensity (Girardin and Mudelsee, 2008; Macias Fauria and Johnson, 2008; Kasischke et al., 2010; Turetsky et al., 2011; Mann et al., 2012; Girardin et al., 2013a). The latter is particularly important because more severe burning consumes soil organic matter to greater depth, often to mineral soil, providing conditions that favor recruitment of deciduous species that in some regions of the North American boreal forest replace what was previously evergreen conifer forest (Johnstone et al., 2010; Bernhardt et al., 2011). Fire-mediated composition changes in post-fire succession influence a host of ecosystem feedbacks to climate, including changes in net ecosystem carbon balance (Bond-Lamberty et al., 2007; Goetz et al., 2007; Welp et al., 2007; Euskirchen et al., 2009) as well as albedo and energy balance (Randerson et al., 2006; Jin et al., 2012; O'Halloran et al., 2012). The extent to which the net effect of these feedbacks will exacerbate or mitigate additional warming is not well known over the larger geographic domain of the boreal biome, except via modeling studies that are relatively poorly constrained owing to sparse *in situ* observations.

The vulnerability of the boreal biome to this cascading series of interacting processes (Wolken et al., 2011), and their ultimate influence on climate

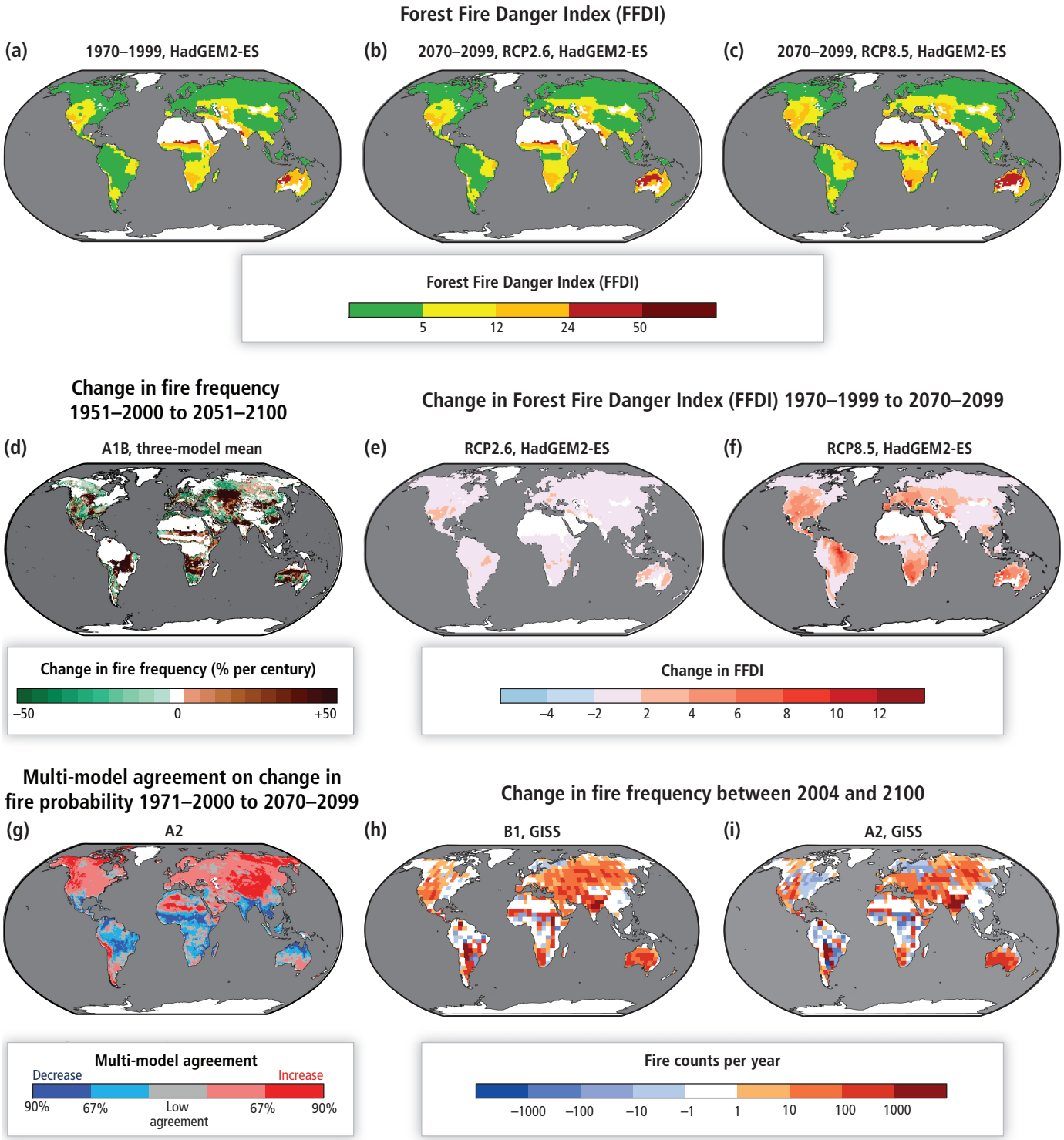


Figure 4-6 | Projected changes in meteorological fire danger, fire probability, and fire frequency with different methods and climate models. (a) 30-year annual mean McArthur Forest Fire Danger Index (FFDI) and change simulated with the Hadley Centre Global Environmental Model version 2 Earth System configuration (HadGEM2-ES) for 1970–1999, with areas of no vegetation excluded (Betts et al., 2013). (b) As (a) for 2070–2099, Representative Concentration Pathway 2.6 (RCP2.6). (c) as (a) for 2070–2099, RCP8.5. (d) Change in fire frequency by 2051–2100 relative to 1951–2000, SRES A1B, simulated with the MC1 vegetation model driven by three GCMs (Commonwealth Scientific and Industrial Research Organisation (CSIRO)-Mk3.0, Met Office Hadley Centre Coupled Model version 3 (HadCM3), Model for Interdisciplinary Research On Climate (MIROC) 3.2medres; mean over three simulations; Gonzalez et al., 2010). (e) Difference between (b) and (a): change in FFDI by 2070–2099 relative to 1970–1999 in HadGEM2-ES, RCP2.6. (f) Difference between (c) and (a): change in FFDI by 2070–2099 relative to 1970–1999 in HadGEM2-ES, RCP8.5. (g) Agreement on changes in fire probability by 2070–2099 relative to 1971–2000 (Moritz et al., 2012) simulated with a statistical model using climate projections from 16 Coupled Model Intercomparison Project Phase 3 (CMIP3) GCMs, Special Report on Emission Scenarios (SRES) A2. (h) Change in fire frequency by 2100 relative to 2004, SRES B1, simulated using climate and land cover projections from the Goddard Institute of Space Studies General Circulation Model (GISS GCM) (AR4 version) and Integrated Model to Assess the Global Environment Integrated Assessment Model (IMAGE IAM) (Pechony and Shindell, 2010). (i) As (h) for SRES A2. Changes in FFDI (a), (b), (c), (e), (f) and fire probability (g) arise entirely from changes in meteorological quantities, whereas changes in fire frequency (d), (h), (i) depend on both meteorological quantities and vegetation.

feedbacks, differs between North America and northern Eurasia (*high confidence*). The latter is dominated by deciduous conifer (larch) forest, extending from western Russia across central to eastern Siberia—a region more than twice the size of the North American boreal biome, most of it underlain by permafrost. In terms of post-fire succession analogous to the North American boreal biome, larch function more like deciduous species than evergreen conifers, with greater density and biomass gain in more severely burned areas, given adequate seed survival through fire events or post-fire seed dispersal (Zyryanova, 2007; Osawa et al., 2010; Alexander et al., 2012). Although the fire regime has intensified in the last 100 years in Siberia, as well as in parts of North America (Soja et al., 2007; Ali et al., 2012; Mann et al., 2012; Marlon et al., 2013), the likelihood of regime shifts in larch forests is currently unknown, partly because larch are self-replacing (albeit at different densities) and partly because it is largely dependent on the fate of permafrost across the region. In summary, an increase in tree mortality is observed in many boreal forests, with the clearest indicators of this in North America. However, tree health in boreal forests varies greatly among regions, which coupled with insufficient temporal coverage means that there is *low confidence* in the detection and attribution of a clear temporal trend in tree mortality at the global scale (Figure 4-4).

The vulnerability of permafrost to thawing and degradation with climate warming is critical not only for determining the rate of a boreal-tundra biome shift and its associated net feedback to climate, but also for predicting the degree to which the mobilization of very large carbon stores frozen for centuries could provide additional warming (*high confidence*; Schuur et al., 2008, 2009, 2013; Tarnocai et al., 2009; Romanovsky et al., 2010; Schaefer et al., 2011; see WGI AR5 Chapters 6 and 12; see also Section 4.3.3.4). The extent and rate of permafrost degradation varies with temperature gradients from warmer discontinuous permafrost areas to colder, more continuous areas, but also with the properties of the soil composition and biology (e.g., Mackelprang et al., 2011). The degree of thermokarsting (melting of ice-rich soil) associated with different substrates and associated topographic relief is variable because boreal vegetation in later successional stages (evergreen conifers in North America) insulates permafrost from air temperature increases; soils with differing silt and gravel content tend to have different ice content that, when melted, produces different degradation and deformation rates; and because of other factors such as the reduction of insulation provided by vegetation cover and soil organic layers due to increased fire (Jorgenson et al., 2010; Grosse et al., 2011). This variability and vulnerability is poorly represented in ESMs (McGuire et al., 2012) and is thus the emphasis of research initiatives currently underway. Carbon management strategies to keep permafrost intact, for example, by removing forest cover to expose the land surface to winter temperatures (Zimov et al., 2009), are impractical, not only because of the vast spatial domain underlain by permafrost, but also because of the broad societal and ecological impacts that would result.

4.3.3.1.2. Temperate forests

The largest areas of temperate forest are found in eastern North America, Europe, and eastern Asia. The overall trend for forests in these regions has until recently been an increase in growth rates of trees and in total carbon stocks. This has been attributed to a combination of increasing growing season length, rising atmospheric CO_2 concentrations, nitrogen deposition, and forest management—specifically regrowth following formerly more intensive harvesting regimes (Ciais et al., 2008). The relative contribution of these factors has been the subject of substantial and unresolved debate (Boisvenue and Running, 2006). Most temperate forests are managed such that any change is and will be to a large extent anthropogenic.

The world's temperate forests act as an important carbon sink (*high confidence* due to *robust evidence* and *high agreement*), absorbing 0.70 ± 0.08 PgC yr^{-1} from 1990 to 1999 and 0.80 ± 0.09 from 2000 to 2007 (Pan et al., 2011).This represents 34% of global carbon accumulation in intact forests and 65% of the global net forest carbon sink (total sink minus total emissions from land use).

Recent indications are that temperate forests and trees are beginning to show signs of climate stress, including a reversal of tree growth enhancement in some regions (North America: Silva et al., 2010; Silva and Anand, 2013; Europe: Charru et al., 2010; Bontemps et al., 2011; Kint et al., 2012); increasing tree mortality (Allen, C.D. et al., 2010; Box 4-2); and changes in fire regimes, insect outbreaks, and pathogen attacks (Adams et al., 2012; Edburg et al., 2012). In northeastern France, widespread recent declines in growth rates of European beech (*Fagus sylvatica* L.) have been attributed to decreasing water availability (Charru et al., 2010). These trends threaten the substantial role of temperate forests as net carbon sinks, but it is still unclear to what extent the observations are representative for temperate forests as a whole. Several studies find that tree growth rates in temperate forests passed their peak in the late 20th century and that the decline in tree growth rates can be attributed to climatic factors, especially drought or heat waves (Charru et al., 2010; Silva et al., 2010). Extreme climate events have had a major impact on temperate forests over the last decade (Ciais et al., 2005; Witte et al., 2011; Kasson and Livingston, 2012). Extensive forest fires occurred in Russia during the exceptionally hot and dry summer of 2010 (Witte et al., 2011). The complex interactions between climate and forest management in determining susceptibility to extreme events make it difficult to unequivocally attribute these events to recent climate warming (Allen, C.D. et al., 2010). There is *low confidence* (*limited evidence*, *medium agreement*) that climate change is threatening the temperate forest carbon sink directly or indirectly.

At the biome level, there remains considerable uncertainty in the sign and the magnitude of the carbon cycle response of temperate forests to climate change. A comparison of Dynamic Global Vegetation Models (DGVMs) showed that for identical end of 21st century climate projections, temperate forests are variously projected to substantially increase in total (biomass plus soil) carbon storage, especially through gains in forest cover; or decrease due to reductions in total carbon storage per hectare and loss of tree cover (Sitch et al., 2008). Projections for eastern Asia are less variable: temperate forests remain carbon sinks over the coming century, with carbon storage generally peaking by mid-century and then declining (Sitch et al., 2008; Peng et al., 2009; Ni, 2011). However, regional vegetation models for China predict a substantial northward shift of temperate forest (Weng and Zhou, 2006; Ni, 2011). There is little indication from either models or observations that the responses of temperate forests to climate change

Box 4-2 | Tree Mortality and Climate Change

Extensive tree mortality and widespread forest dieback (high mortality rates at a regional scale) linked to drought and temperature stress have been documented recently on all vegetated continents (Allen, C.D. et al., 2010; Figure 4-7). However, appropriate field data sets are currently lacking for many regions (Anderegg et al., 2013a), leading to *low confidence* in our ability to detect a global trend. Nevertheless, long-term increasing tree mortality rates associated with temperature increases and drought have been documented in boreal and temperate forests in western North America (van Mantgem et al., 2009; Peng et al., 2011). Increased levels of tree mortality following drought episodes have also been detected in multiple tropical forests (Kraft et al., 2010; Phillips et al., 2010) and Europe (Carnicer et al., 2011). Episodes of widespread dieback (high mortality rates at a regional scale) have been observed in multiple vegetation types, particularly in western North America, Australia, and southern Europe (Raffa et al., 2008; Carnicer et al., 2011; Anderegg et al., 2013a). Some widespread dieback events have occurred concomitant with infestation outbreaks (Hogg et al., 2008; Raffa et al., 2008; Michaelian et al., 2011), where insect populations are also directly influenced by climate, such as population release by warmer winter temperatures (Bentz et al., 2010). Although strong attribution of extensive tree mortality to recent warming has been made in a few studies, the paucity of long-term studies of the mechanisms driving mortality means that there is low confidence that this attribution can be made at the global scale.

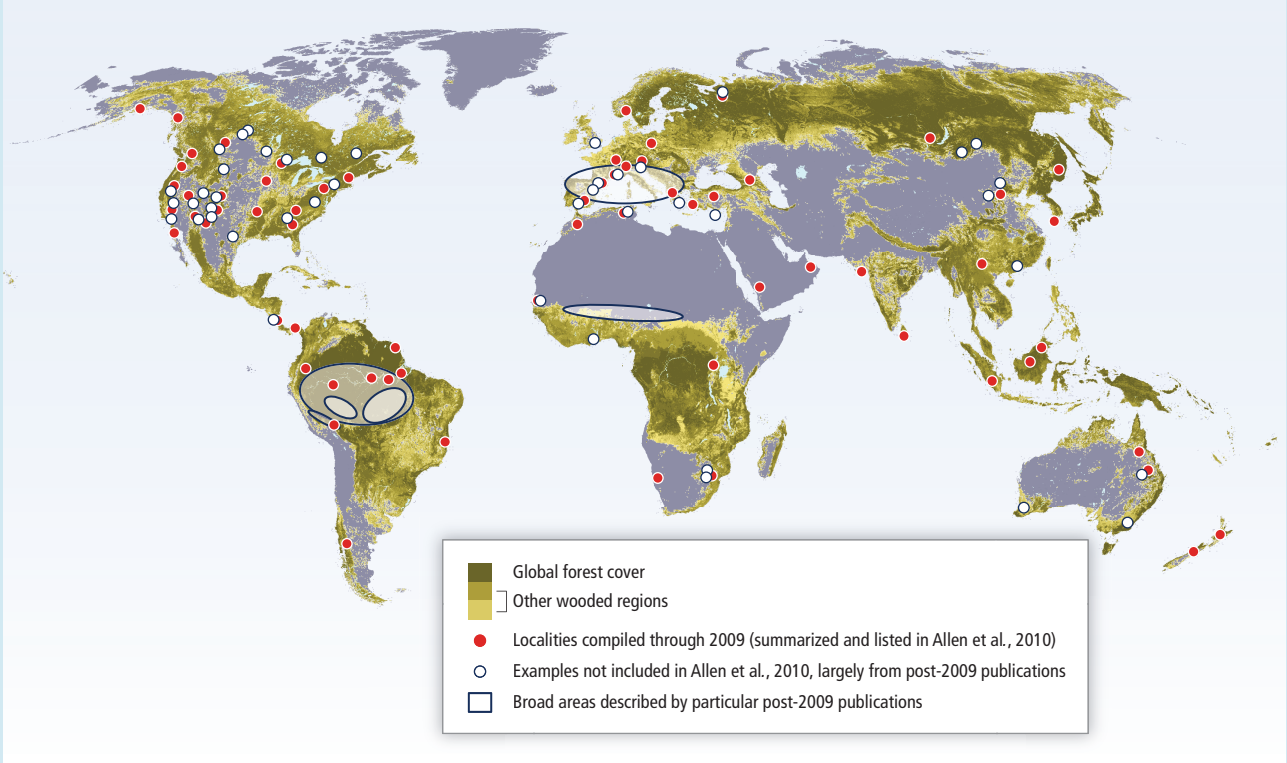


Figure 4-7 | Locations of substantial drought- and heat-induced tree mortality around the globe since 1970 (global forest cover and other wooded regions based on FAO, 2005). Studies compiled through 2009 (red dots) are summarized and listed in Allen, C.D. et al. (2010). Localities and measurement networks not included in Allen, C.D. et al. (2010), which are largely from post-2009 publications, have been added to this map (white dots and shapes). New locality references by region: Africa: Mehl et al., 2010; van der Linde et al., 2011; Fauset et al., 2012; Gonzalez et al., 2012; Kherchouche et al., 2012; Asia: Dulamsuren et al., 2009; Kharuk et al., 2013; Liu et al., 2013; Zhou et al., 2013; Australasia: Brouwers et al., 2012; Fensham et al., 2012; Keith et al., 2012; Matusick et al., 2012; Brouwers et al., 2013; Matusick et al., 2013; Europe: Innes, 1992; Peterken and Mountford, 1996; Linares et al., 2009; Galiano et al., 2010; Vennetier and Ripert, 2010; Aakala et al., 2011; Carnicer et al., 2011; Linares et al., 2011; Sarris et al., 2011; Marini et al., 2012; Cailleret et al., 2013; Vilà-Cabrera et al., 2013; North America: Fahey, 1998; Minnich, 2007; Klos et al., 2009; Ganey and Vojta, 2011; Michaelian et al., 2011; Peng et al., 2011; DeRose and Long, 2012; Fellows and Goulden, 2012; Kaiser et al., 2012; Millar et al., 2012; Garrity et al., 2013; Kukowski et al., 2013; Williams et al., 2013; Worrall et al., 2013; South America: Enquist and Enquist, 2011; Lewis et al., 2011; Saatchi et al., 2013.

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Box 4-2 (continued)

Forest dieback has influenced the species composition, structure and age demographics, and successional trajectories in affected forests, and in some cases led to decreased plant species diversity and increased risk of invasion (Kane et al., 2011; Anderegg et al., 2012). Widespread tree mortality also has multiple effects on biosphere-atmosphere interactions and could play an important role in future carbon-cycle feedbacks through complex effects on forest biophysical properties and biogeochemical cycles (Breshears et al., 2005; Kurz et al., 2008; Anderson et al., 2011).

Projections of tree mortality due to climate stress and potential thresholds of widespread forest loss are currently highly uncertain (McDowell et al., 2011). Most current vegetation models have little-to-no mechanistic representation of tree mortality (Fisher et al., 2010; McDowell et al., 2011). Nonetheless, a global analysis of tree hydraulic safety margins found that 70% of surveyed tree species operate close to their limits of water stress tolerance (Choat et al., 2012), indicating that vulnerability to drought and temperature stress will not be limited to arid and semiarid forests. Furthermore, time scales of tree and plant community recovery following drought are largely unknown, but preliminary evidence from several forests indicates that full recovery times may be longer than drought return intervals, leading to "compounding" effects of multiple droughts (Mueller et al., 2005; Anderegg et al., 2013b; Saatchi et al., 2013). Projected increases in temperature are also expected to facilitate expansion of insect pest outbreaks poleward and in altitude, which may also cause or contribute to tree mortality (Bentz et al., 2010).

are characterized by tipping points (Bonan, 2008). There is *low confidence* (*medium evidence*, *low agreement*) on long-term, climate-driven changes in temperate forest biomass and geographical range shifts.

At the species level, models predict that the potential climatic space for most tree species will shift poleward and to higher altitude in response to climate change (Dale et al., 2010; Ogawa-Onishi et al., 2010; Hickler et al., 2012). Associated long-term projected range shifts generally vary from several kilometers to several tens of kilometers per decade, most probably faster than natural migration (e.g., Chmura et al., 2011; see also Section 4.3.2.5). Therefore, assisted migration has been suggested as an adaptation measure (see Section 4.4.2.4). Such shifts would alter biodiversity and ecosystem services from temperate forests (e.g., Dale et al., 2010). Multi-model comparisons for temperate forests, however, illustrate that there are differences in species response and that models differ greatly in the severity of projected climate change impacts on species ranges (Morin and Thuiller, 2009; Kearney et al., 2010; Kramer et al., 2010; Cheaib et al., 2012). Tree growth models project increased tree growth at the poleward and high altitudinal range limits over most of the 21st century in China (Ni, 2011). New approaches to modeling tree responses, based on the sensitivity of key life-history stages, suggest that climate change impacts on reproduction could be a major limitation on temperate tree distributions (Morin et al., 2007). Comparisons with paleoecological data have helped improve confidence in the ability of models to project future changes in species ranges (Pearman et al., 2008; Allen, J.R.M. et al., 2010; Garreta et al., 2010). Model projections are qualitatively coherent with observations that temperate forest species are moving up in altitude, probably due to climate warming at the end of the 20th century (Lenoir et al., 2008). There is *medium confidence* (*medium evidence*, *medium agreement*) that temperate tree species are migrating poleward and to higher altitudes.

4.3.3.1.3. Tropical forests

Climate change effects on tropical forests interact with the direct influences of humans and are understood largely through field studies of the responses of forests to extreme weather events and through models that are able to simulate a growing number of ecological and atmospheric processes (Malhi et al., 2008; Davidson et al., 2012).

A key uncertainty in our understanding of future impacts of climate change on tropical forests is the strength of direct CO_2 effects on photosynthesis and transpiration (see Section 4.3.2.4). These responses will play an important role in determining tropical forest trends as temperatures and atmospheric CO_2 concentrations rise. There is a physiological basis for arguing that photosynthesis will increase sufficiently to offset the inhibitory effects of higher temperatures on forest productivity (Lloyd and Farquhar, 2008), although heightened photosynthesis does not necessarily translate into an increase in overall forest biomass (Körner and Basler, 2010). DGVMs and the current generation of ESMs, including those used within CMIP5 (e.g., Jones et al., 2011; Powell et al., 2013), generally use formulations for CO_2 effects on photosynthesis and transpiration based on laboratory-scale work (Jarvis, 1976; Farquhar et al., 1980; Ball et al., 1987; Stewart, 1988; Collatz et al., 1992; Leuning, 1995; Haxeltine and Prentice, 1996; Cox et al., 1998) that predates larger ecosystem-scale studies, although some models have been calibrated on the basis of more recent data (Jones et al., 2011).

A second important source of uncertainty is the rate of future CO_2 rise and climate change (Betts et al., 2012). Modeled simulations of future climate in tropical forest regions indicate with *high confidence* (*robust evidence*, *high agreement*) that temperature will increase. Future precipitation change, in contrast, is highly uncertain and varies considerably between

climate models (WGI AR5 Annex 1: Atlas of Global and Regional Climate Projections), although there is *medium confidence* (*medium evidence*, *medium agreement*) that some tropical regions, such as the eastern Amazon Basin, will experience lower precipitation and more severe drought (Malhi et al., 2009a; Shiogama et al., 2011). The range of possible shifts in the moist tropical forest envelope is large, sensitive to the responsiveness of water use efficiency (WUE) to rising concentrations of atmospheric CO_2, and varies depending on the climate and vegetation model that is used (Scholze et al., 2006; Sitch et al., 2008; Zelazowski et al., 2011). Recent model studies (Malhi et al., 2009a; Cox et al., 2013; Huntingford et al., 2013) indicate that the future geographical range of moist tropical forests as determined by its shifting climatological envelope is less likely to undergo major retractions or expansions by 2100 than was suggested in AR4. Since AR4, there is new evidence of more frequent severe drought episodes in the Amazon region that are associated with sea surface temperature increases in the tropical North Atlantic (*medium confidence*; Marengo et al., 2011). There is *low confidence*, however, that these droughts or the observed sea surface temperatures can be attributed to climate change.

Networks of long-term forest plots reveal that lianas and fast-growing tree species are increasing, as is forest biomass (Phillips et al., 2002, 2005; Lewis et al., 2009a,b, 2011). Faster tree growth is consistent with increasing WUE associated with the rising concentration of CO_2, but also with changes in solar radiation and the ratio of diffuse to direct radiation (Lewis et al., 2009a; Mercado et al., 2009; Brando et al., 2010; see also Section 4.2.4.5). There is *low confidence* (*limited evidence*, *medium agreement*) that the composition and biomass of Amazon and African forests are changing through the rise in atmospheric CO_2. The potential suppression of photosynthesis and tree growth in tropical forests through rising air temperatures is supported by physiological and eddy covariance studies (Doughty and Goulden, 2008; Lloyd and Farquhar, 2008; Wood et al., 2012), but is not yet observed as changes in forest biomass (except Clark et al., 2003).

Since AR4, there is new experimental and observational evidence of ecological thresholds of drought and fire in moist tropical forests that points to an important indirect role of climate change in driving large-scale changes in these ecosystems, and to the importance of extreme drought events (see Box 4-3). Forest tree mortality increased abruptly above a critical level of soil moisture depletion in two rainfall exclusion experiments (Nepstad et al., 2007; Fisher et al., 2008) and above a critical level of weather-related fire intensity in a prescribed burn experiment (Brando et al., 2012). These experimental results were corroborated by observations of increased tree mortality during the severe 2005 drought in the Amazon (Phillips et al., 2009) and extensive forest fire (Alencar et al., 2006, 2011; Aragão et al., 2008; Box 4-3). There is *high confidence* (*medium evidence*, *high agreement*) that moist tropical forests have many tree species that are vulnerable to drought- and fire-induced mortality during extreme dry periods.

There is also a growing body of evidence that severe weather events interact with land use to influence moist tropical forest fire regimes. Many moist tropical forests are not susceptible to fire during typical rainfall years because of high moisture content of fine fuels (Cochrane, 2003). Selective logging, drought, and fire itself can reduce this fire resistance by killing trees, thinning the canopy, and allowing greater heating of the forest interior (Uhl and Kauffman, 1990; Curran et al., 2004; Ray et al., 2005; Box 4-3). Land use also often increases the ignition sources in tropical landscapes (Silvestrini et al., 2011). These relationships are not yet represented fully in coupled climate-vegetation models. There is *high confidence* (*robust evidence*, *high agreement*) that forest fire frequency and severity is increasing through the interaction between severe droughts and land use. There is *medium confidence* (*medium evidence*, *high agreement*) that tree mortality in the Amazon region is increasing through severe drought and increased forest fire occurrence and *low confidence* that this can be attributed to warming (Figure 4-4).

Dry tropical forests are defined by strong seasonality in rainfall distribution (Mooney et al., 1995) and have been reduced to an estimated 1 million km^2 globally through human activities (Miles et al., 2006). Half of the world's remaining dry tropical forests are located in South America. Using five climate model simulations for the 2040–2069 period under the IS92a "business-as-usual scenario," Miles et al. (2006) found that approximately one-third of the remaining area of tropical dry forests in the Americas will be exposed to higher temperatures and lower rainfall through climate change. Climate change, deforestation, fragmentation, fire, or human pressure place virtually all (97%) of the remaining tropical dry forests at risk of replacement or degradation (Miles et al., 2006). In a regional study a dynamic vegetation model (Integrated Biosphere Simulator (IBIS)) under A2 and B2 scenarios projected by a global climate model (Hadley Centre Regional Model 3 (HadRM3)) found that most of the dry forests of India would be outside of their climate envelopes later in this century (Chaturvedi et al., 2011). There is *low confidence* in our understanding of climate change effects on dry forests globally.

4.3.3.2. Dryland Ecosystems: Savannas, Shrublands, Grasslands, and Deserts

The following sections treat a wide range of terrestrial ecosystems covering a large part of the land surface, whose common features are that they typically exhibit strong water stress for several months each year and grass-like plants and herbs are a major part of their vegetation cover. Thus the principal land use often involves grazing by domestic livestock or wild herbivores.

4.3.3.2.1. Savannas

Savannas are mixtures of coexisting trees and grasses, covering about a quarter of the global land surface, including tropical and temperate forms. Savannas are characterized by annual to decadal fires (Archibald et al., 2009) of relatively low intensity, which are an important factor in maintaining the tree-grass proportions (Beerling and Osborne, 2006), but also constitute a major and climate-sensitive global source of fire-related emissions from land to atmosphere (Schultz et al., 2008; van der Werf et al., 2010). The geographical distribution of savannas is determined by temperature, the seasonal availability of water, fire, and soil conditions (Ellery et al., 1991; Walker and Langridge, 1997; Staver et al., 2011) and is therefore inferred to be susceptible to climate change. In parts of Central Africa, forests have been observed to be

Box 4-3 | A Possible Amazon Basin Tipping Point

Since AR4, our understanding of the potential of a large-scale, climate-driven, self-reinforcing transition of Amazon forests to a dry stable state (known as the Amazon "forest dieback") has improved. Modeling studies indicate that the likelihood of a climate-driven forest dieback by 2100 is lower than previously thought (Malhi et al., 2009b; Cox et al., 2013; Good et al., 2013; Huntingford et al., 2013), although lower rainfall and more severe drought is expected in the eastern Amazon (Malhi et al., 2009a). There is now *medium confidence* (*medium evidence*, *medium agreement*) that climate change alone (i.e., through changes in the climate envelope, without invoking fire and land use) will not drive large-scale forest loss by 2100 although shifts to drier forest types are predicted in the eastern Amazon (Mahli et al., 2009a). Meteorological fire danger is projected to increase in some models (Golding and Betts, 2008; Betts et al., 2013; Figure 4-6). Field studies and regional observations have provided new evidence of critical ecological thresholds and positive feedbacks between climate change and land use activities that could drive a fire-mediated, self-reinforcing dieback during the next few decades (Figure 4-8). There is now *medium confidence* (*medium evidence*, *high agreement*) that severe drought episodes, land use, and fire interact synergistically to drive the transition of mature Amazon forests to low-biomass, low-statured fire-adapted woody vegetation.

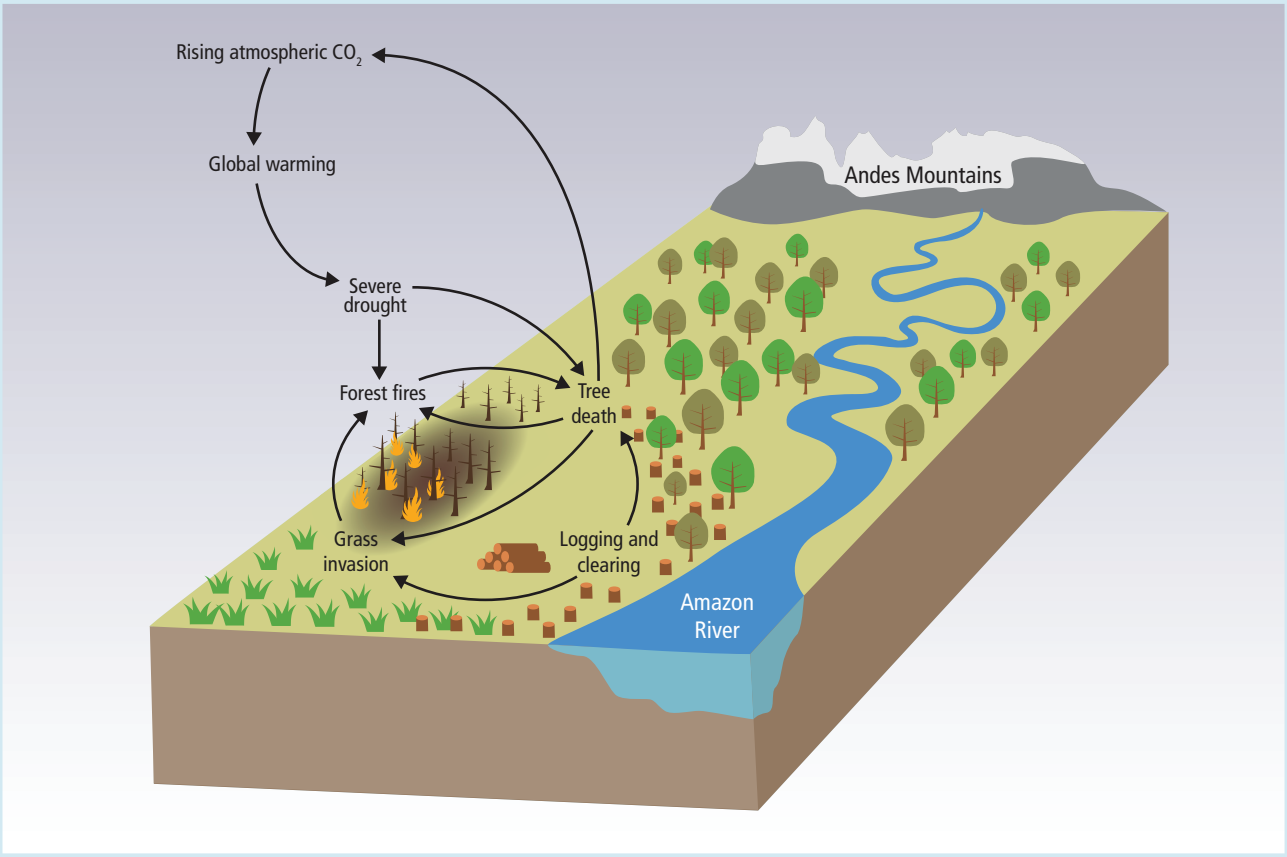

Figure 4-8 | The forests of the Amazon Basin are being altered through severe droughts, land use (deforestation, logging), and increased frequencies of forest fire. Some of these processes are self-reinforcing through positive feedbacks, and create the potential for a large-scale tipping point. For example, forest fire kills trees, increasing the likelihood of subsequent burning. This effect is magnified when tree death allows forests to be invaded by flammable grasses. Deforestation provides ignition sources to flammable forests, contributing to this dieback. Climate change contributes to this tipping point by increasing drought severity, reducing rainfall and raising air temperatures, particularly in the eastern Amazon Basin (*medium confidence*; *medium evidence*, *medium agreement*).

Continued next page →

Box 4-3 (continued)

Most primary forests of the Amazon Basin have damp fine fuel layers and low susceptibility to fire, even during annual dry seasons (Uhl and Kauffman, 1990; Ray et al., 2005). Forest susceptibility to fire increases through canopy thinning and greater sunlight penetration caused by tree mortality associated with selective logging (Uhl and Kauffman, 1990; Ray et al., 2005; Barlow and Peres, 2008), previous forest fire (Balch et al., 2008; Brando et al., 2012), severe drought (Alencar et al., 2006), or drought-induced tree mortality (Nepstad et al., 2007; da Costa et al., 2010). The impact of fire on tree mortality is also weather dependent. Under very dry, hot conditions, fire-related tree mortality can increase sharply (Brando et al., 2012). Under some circumstances, tree damage is sufficient to allow light-demanding, flammable grasses to establish in the forest understory, increasing forest susceptibility to further burning (Veldman and Putz, 2011). There is *high confidence* (*robust evidence*, *high agreement*) that logging, severe drought, and previous fire increase Amazon forest susceptibility to burning.

Landscape level processes further increase the likelihood of forest fire. Fire ignition sources are more common in agricultural and grazing lands than in forested landscapes (Silvestrini et al., 2011) (*high confidence*: *robust evidence*, *high agreement*), and forest conversion to grazing and crop lands can inhibit regional rainfall through changes in albedo and evapotranspiration (Costa et al., 2007; Butt et al., 2011; Knox et al., 2011) (*low confidence*: *medium evidence*, *low agreement*) or through smoke, which can inhibit rainfall under some circumstances (Andreae et al., 2004) (*medium confidence*: *medium evidence*, *medium agreement*). Apart from these landscape processes, climate change could increase the incidence of severe drought episodes (Mahli et al. 2009b; Shiogama et al., 2011).

If recent patterns of deforestation (through 2005), logging, severe drought, and forest fire continue into the future, more than half of the region's forests will be cleared, logged, burned, or exposed to drought by 2030, even without invoking positive feedbacks with regional climate, releasing 20 ± 10 PgC to the atmosphere (Nepstad et al., 2008) (*low confidence*: *low evidence*, *medium agreement*) (Figure 4-8). The likelihood of a tipping point being reached may decline if extreme droughts (such as 1998, 2005, and 2010) (Marengo et al., 2011) become less frequent, if land management fires are suppressed, if forest fires are extinguished on a large scale (Soares-Filho et al., 2012), if deforestation declines, or if cleared lands are reforested (Nepstad et al., 2008). The 77% decline in deforestation in the Brazilian Amazon with 80% of the region's forest still standing (INPE, 2013) demonstrates that policy-led avoidance of a fire-mediated tipping point is plausible.

moving into adjacent savannas and grasslands (Mitchard et al., 2009), possibly due to depopulation and changes in the fire regime. In northern Australia, forest is expanding into former savanna areas (Brook and Bowman, 2006; Bowman et al., 2011; Tng et al., 2012). It has been projected that drying and greater seasonality, acting in conjunction with increased fire, could lead to former forested areas becoming savannas in parts of the Amazon basin (Malhi et al., 2009b; Box 4-3). In many places around the world the savanna boundary is moving into former grasslands on elevation gradients; in other words, into areas inferred to be formerly too cool for trees (Breshears, 2006).

The proportion of trees and grasses in savannas is considered unstable under some conditions (De Michele et al., 2011; Staver et al., 2011). The differential effects of climate change, rising CO_2, fire, and herbivory on trees and grasses have the potential to alter the tree cover in savannas, possibly abruptly. There is evidence from many parts of the world that the tree cover and biomass in savannas has increased over the past century and in some places, on all continents, continues to do so (*robust evidence*, *high agreement*; Moleele et al., 2002; Angassa and Oba, 2008; Cabral et al., 2009; Wigley et al., 2009; Witt et al., 2009; Lunt et al., 2010; Rohde and Hoffman, 2012). The general consequences are more carbon stored per unit land area in form of tree biomass and soil organic matter (Hughes et al., 2006; Liao et al., 2006; Knapp et al., 2007; Throop and Archer, 2008; Boutton et al., 2009), changes in hydrology (Muñoz-Robles et al., 2011), and reduced grazing potential (Scholes and Archer, 1997). Increasing tree cover in savannas has been attributed to changes in land management (Joubert et al., 2008; Van Auken, 2009), rising CO_2 (Bond and Midgley, 2012; Buitenwerf et al., 2012), climate variability and change (Eamus and Palmer, 2007; Fensham et al., 2009), or several of these factors acting in combination (Ward, 2005). As yet, there are no studies that definitively attribute the relative importance of the climate- and non-climate-related causes of woody plant biomass increase in savannas (and the invasion of trees into former grasslands), but there is *medium agreement* and *robust evidence* that climate change and rising CO_2 are contributing factors in many cases. The increased growth rate of C_3 photosynthetic system trees relative to C_4

grasses under rising CO_2 could relieve the demographic bottleneck that keeps trees trapped within the flame zone of the grasses, a hypothesis supported by elevated CO_2 experiments with savanna saplings (Kgope et al., 2010).

A model of grasslands, savannas, and forests suggests that rising CO_2 does increase the likelihood of abrupt shifts to woodier states, but the transition will take place at different CO_2 concentrations in different environments (Higgins and Scheiter, 2012). On the other hand, observation of contrasts in the degree of savanna thickening between land parcels with the same CO_2 exposure but different land use histories, topographic position, or soil depth (Wiegand et al., 2005; Wu and Archer, 2005) imply that land management, water balance, and microclimate are also important. Tree cover in savannas is rainfall-constrained (Sankaran et al., 2005), suggesting that future increases in rainfall projected for most but not all savanna areas (WGI AR5 Annex I: Atlas of Global and Regional Climate Projections) could lead to increased tree biomass.

4.3.3.2.2. Grasslands and shrublands

Rangelands (partly overlapping with savannas) cover approximately 30% of the Earth's ice-free land surface and hold an equivalent amount of the world's terrestrial carbon (Booker et al., 2013). Much evidence from around the world shows that dry grasslands and shrublands are highly responsive in terms of primary production, species composition, and carbon balance to changes in water balance (precipitation and evaporative demand) within the range of projected climate changes (*high confidence*) (e.g., Sala et al., 1988; Snyman and Fouché, 1993; Fay et al., 2003; Peñuelas et al., 2004, 2007; Prieto et al., 2009; Peters et al., 2010; Martí-Roura et al., 2011; Booker et al., 2013; Wu and Chen, 2013). Rainfall amount and timing have large effects on a wide range of biological processes in grasslands and shrublands, including seed germination, seedling establishment, plant growth, flowering time, root mass, community composition, population and community dynamics production, decomposition and respiration, microbial processes and carbon, plant, and soil nutrient contents (e.g., Fay et al., 2003; Peñuelas et al., 2004, 2007; Beier et al., 2008; Sardans et al., 2008a,b; Sowerby et al., 2008; Liu et al., 2009; Miranda et al., 2009; Albert et al., 2011, 2012; Selsted et al., 2012; Walter et al., 2012).

Precipitation changes were as important for mountain flora in Europe as temperature changes, and the greatest composition changes will probably occur when decreased precipitation accompany warming (Engler et al., 2011). Responses of shrublands to drought may be driven partly by changes in the soil microbial community (Jensen et al., 2003) or changes in soil fauna (Maraldo et al., 2008). An increase in drought frequency, without an increase in drought severity, leads to loss of soil carbon in moist, carbon-rich moorlands, due to changes in soil structure or soil microbial community leading to increased hydrophobicity and soil respiration (Sowerby et al., 2008, 2010). Simulated increased spring temperature and decreased summer precipitation had a general negative effect on plant survival and plant growth, irrespective of the macroclimatic niche characteristics of the species. Against expectation, species with ranges extending into drier regions did not generally perform better under drier conditions (Bütof et al., 2012).

Changing climate and land use have resulted in increased aridity and a higher frequency of droughts in drylands around the world, with increasing dominance of abiotic controls of land degradation (in contrast to direct human- or herbivore-driven degradation) and changes in hydrology and the erosion of soil by wind (Ravi et al., 2010). In mixed shrub grasslands, the influence of drought periods could produce transient pulses of carbon that are much larger than the pulses produced by fire (Martí-Roura et al., 2011). Most studies of changes in arid systems between grasslands and shrublands have focused on plant-soil feedbacks that favor shrub growth. Summers drier than three-quarters of current rainfall decreased grass seedling recruitment to negligible values (Peters et al., 2010). Management cannot reliably increase carbon uptake in arid and semiarid rangelands, which is most often controlled by abiotic factors not easily changed by management of grazing or vegetation (Booker et al., 2013).

Other factors being equal, grasslands and shrublands in cool areas are expected to respond to warming with increased primary production, while those in hot areas are expected to show decreased production (*limited evidence*, *low agreement*). A shift to more woody vegetation states expected to occur (locally but not globally) in tropical grasslands of the African continent (Higgins and Scheiter, 2012). The response to warming and drought depends on site, year, and plant species, as shown by manipulation experiments (Peñuelas et al., 2004, 2007; Gao and Giorgi, 2008; Grime et al., 2008; Shinoda et al., 2010; Wu and Chen, 2013). In most temperate and Arctic regions, the capacity to support richer (i.e., more diverse) communities is projected to increase with rising temperature, while decreases in water availability suggest a decline in capacity to support species-rich communities in most tropical and subtropical regions (Sommer et al., 2010). Warming may cause an asymmetrical response of soil carbon and nitrogen cycles, causing nitrogen limitation that reduces acclimation in plant production (Beier et al., 2008).

Some grasslands are exposed to elevated levels of nitrogen deposition, which alters species composition, increases primary production up to a point, and decreases it thereafter (see Section 4.2.4.2; Bobbink et al., 2010; Cleland and Harpole, 2010; Gaudnik et al., 2011). In a study of 162 plots over 25 years, nitrogen deposition drove grassland composition at the local scale, in interaction with climate, whereas climate changes were the predominant driver at the regional scale (Gaudnik et al., 2011). Nitrogen mineralization in shrublands under either arid or wet conditions is more sensitive to periodic droughts than systems under more mesic conditions (Emmett et al., 2004). Decreased tissue concentrations of phosphorus were also associated with warming and drought (Peñuelas et al., 2004, 2012; Beier et al., 2008). Strong interactions between warming and disturbances have been observed, leading to increased nitrogen leaching from shrubland ecosystems (Beier et al., 2004).

Most grasslands and shrublands are characterized by relatively frequent but low-intensity fires, which affect their plant species composition and demographics (e.g., Gibson and Hulbert, 1987; Gill et al., 1999; Uys et al., 2004; de Torres Curth et al., 2012). Species composition changes may be as important in determining ecosystem impacts as the direct effects of climate on plant (Suttle et al., 2007). Fire frequency, duration, and intensity are influenced primarily by climate and secondarily by management (Pitman et al., 2007; Lenihan et al., 2008; Archibald et al.,

2009; Giannakopoulos et al., 2009; Armenteras-Pascual et al., 2011), and are therefore sensitive to climate change; the duration of the fire season is also projected to broaden (Clarke et al., 2013). Changes in fire frequency may interact with changes in rainfall seasonality: for instance, if fires are followed by rainy spring periods in northwestern Patagonia, as occurs with more frequent El Niño-Southern Oscillation (ENSO) phenomena, there are more recruitment windows for shrubs (Ghermandi et al., 2010). Relatively little is known regarding the combined effect of climate change and increased grazing by large mammals, or on the consequences for pastoral livelihoods that depend on rangelands (Thornton et al., 2009).

4.3.3.2.3. Deserts

The deserts of the world, defined as land areas with an arid or hyperarid climate regime, occupy 35% of the global land surface. Species composition in desert areas is expected to shift in response to climate warming (Ooi et al., 2009; Kimball et al., 2010). Deserts are sparsely populated, but the people who do live there are among the poorest in the world (Millennium Ecosystem Assessment, 2005a). There is *medium agreement* but *limited evidence* that the present extent of deserts will increase in the coming decades, despite the projected increase in rainfall at a global scale, as a result of the strengthening of the Hadley Circulation, which determines the location of the broad band of hot deserts approximately 15°N to 30°N and 15°S to 30°S of the equator (Mitas and Clement, 2005; Seidel et al., 2008; Johanson and Fu, 2009; Lu et al., 2009; Zhou et al., 2011). There may be a feedback to the global climate from an increase in desert extent, which differs in sign between deserts closer to the equator than 20° and those closer to the pole: in model simulations, extension of the near-equator "hot deserts" causes warming, while extension of the near-boreal "cold deserts" causes cooling, in both cases largely through albedo-mediated effects (Alkama et al., 2012). Deserts are expected to become warmer and drier at faster rates than other terrestrial regions (Lapola et al., 2009; Stahlschmidt et al., 2011). Most deserts are already extremely hot, and therefore further warming likely to be physiologically injurious rather than beneficial. The ecological dynamics in deserts are rainfall event-driven (Holmgren et al., 2006), often involving the concatenation of a number of quasi-independent events. Some desert tolerance mechanisms (e.g., biological adaptations by long-lived taxa) may be outpaced by global climate change (Lapola et al., 2009; Stahlschmidt et al., 2011).

4.3.3.2.4. Mediterranean-type ecosystems

Mediterranean-type ecosystems occur on most continents, and are characterized by cool, wet winters and hot, dry summers. They were identified as being among the most likely to be impacted by climate change in AR4 and received extensive coverage (Fischlin et al., 2007). Since then, further evidence has accumulated of climate risks to these systems from rising temperature (Giorgi and Lionello, 2008), rainfall change (declining in most but not all cases), increased drought (Sections 23.2.3, 25.2), and increased fire frequency (Section 23.4.4). There have been observed shifts in phenology (Gordo and Sanz, 2010), range contraction of Mediterranean species (Pauli et al., 2012), declines in the health and growth rate of dominant tree species (Allen, C.D. et al., 2010; Sarris et al., 2011; Brouwers et al., 2012; see also Section 23.4.4), and increased risk of erosion and desertification, especially in very dry areas (Lindner et al., 2010; Shakesby, 2011). Model projections show further species range contractions in the 21st century under all climate change scenarios. This will result in losses of biodiversity (*medium confidence*) (Maiorano et al., 2011; Kuhlmann et al., 2012; see also Sections 23.6.4, 25.1).

4.3.3.3. Rivers, Lakes, Wetlands, and Peatlands

Freshwater ecosystems are considered to be among the most threatened on the planet (Dudgeon et al., 2006; Vörösmarty et al., 2010). Fragmentation of rivers by dams and the alteration of natural flow regimes have led to major impacts on freshwater biota (Pringle, 2001; Bunn and Arthington, 2002; Nilsson et al., 2005; Reidy Liermann et al., 2012). Floodplains and wetland areas have become occupied for intensive urban and agricultural land use to the extent that many are functionally disconnected from their rivers (Tockner et al., 2008). Pollution from cities and agriculture, especially nutrient loading, has resulted in declines in water quality and the loss of essential ecosystem services (Allan, 2004). As a direct consequence of these and other impacts, freshwaters have some of the highest rates of extinction of any ecosystem for those species groups assessed for the IUCN Red List (estimated as much as 4% per decade for some groups, such as crayfish, mussels, fishes, and amphibians in North America) (Dudgeon et al., 2006), with estimates that roughly 10,000 to 20,000 freshwater species are extinct or imperilled as a consequence of human activity (Strayer and Dudgeon, 2010). This is a particular concern given that freshwater habitats support 6% of all described species (Dudgeon et al., 2006), including approximately 40% of the world's fish diversity and a third of the vertebrate diversity (Balian et al., 2008).

It is *very likely* that these stressors to freshwater ecosystems will continue to dominate as human demand for water resources grows, accompanied by increased urbanization and expansion of irrigated agriculture (Vörösmarty et al., 2000; Malmqvist et al., 2008; Dise, 2009). However, climate change will have significant additional impacts (*high confidence*), from altered thermal regimes, altered precipitation and flow regimes, and, in the case of coastal wetlands, sea level rise. Specific aquatic habitats that are most vulnerable to these direct climate effects, especially rising temperatures, are those at high altitude and high latitude, including Arctic and sub-Arctic bog communities on permafrost, and alpine and Arctic streams and lakes (see Section 4.3.3.4; Klanderud and Totland, 2005; Smith et al., 2005; Smol and Douglas, 2007b). It is noteworthy that these high-latitude systems currently experience a relatively low level of threat from other human activities (Vörösmarty et al., 2010). It is likely that the shrinkage and disappearance of glaciers will lead to the reduction of local and regional freshwater biodiversity, with 11 to 38% of the regional macroinvertebrate species pool expected to be lost following complete disappearance of glaciers (Jacobsen et al., 2012; Box CC-RF). Shrinkage of glaciers and the loss of small glaciers will most likely reduce beta diversity at the species and the genetic level, as predicted for the Pyrenees (Finn et al., 2013). Dryland rivers and wetlands, many already experiencing severe water stress from human consumptive use, are also likely to be further impacted by decreased and more variable

precipitation and higher temperatures. Headwater stream systems in general are also vulnerable to the effects of warming because their temperature regimes closely track air temperatures (Caissie, 2006).

There is widespread evidence of rising stream and river temperatures over the past few decades (Langan et al., 2001; Morrison et al., 2002; Webb and Nobilis, 2007; Chessman, 2009; Ormerod, 2009; Kaushal et al., 2010; van Vliet et al., 2011; Markovic et al., 2013; but see Arismendi et al., 2012). Rising water temperature has been linked by observational and experimental studies to shifts in invertebrate community composition, including declines in cold stenothermic species (Brown et al., 2007; Durance and Ormerod, 2007; Chessman, 2009; Ormerod, 2009). Rising temperature is also implicated in species range shifts (e.g., Comte and Grenouillet, 2013), implying changes in the composition of river fish communities (Daufresne and Boet, 2007; Buisson et al., 2008; Comte et al., 2013), especially in headwater streams where species are more sensitive to warming (e.g., Buisson and Grenouillet, 2009).

Rising temperatures in the well-mixed surface waters in many temperate lakes, resulting in reduced periods of ice formation (Livingstone and Adrian, 2009; Weyhenmeyer et al., 2011) and earlier onset and increased duration and stability of the thermocline during summer (Winder and Schindler, 2004), are projected to favor a shift in dominance to smaller phytoplankton (Parker et al., 2008; Winder et al., 2009; Yvon-Durocher et al., 2011) and cyanobacteria (Wiedner et al., 2007; Jöhnk et al., 2008; Paerl et al., 2011), especially in those ecosystems experiencing high anthropogenic loading of nutrients (Wagner and Adrian, 2009); with impacts to water quality, food webs, and productivity (O'Reilly et al., 2003; Verburg et al., 2003; Gyllström et al., 2005; Parker et al., 2008; Shimoda et al., 2011). Prolonged stratification and associated anaerobic conditions near the sediment-water interface can increase the internal loading of phosphorus, particularly in eutrophic lakes (Søndergaard et al., 2003; Wilhelm and Adrian, 2008; Wagner and Adrian, 2009).

In many freshwater ecosystems, the input of dissolved organic carbon through runoff from the catchment has increased, inducing changes in water color (Hongve et al., 2004; Evans et al., 2005; Erlandsson et al., 2008). Soil recovery from acidification and changed hydrological conditions (partly linked to increased precipitation) appear to be the main factors driving this development (Evans et al., 2005; Monteith et al., 2007). The resulting increased light attenuation can lead to lower algal concentrations and loss of submersed vegetation (Ask et al., 2009; Karlsson et al., 2009).

Emergent aquatic macrophytes are likely to expand their northward distribution and percentage cover in boreal lakes and wetlands, posing an increasing overgrowth risk for sensitive macrophyte species (Alahuhta et al., 2011). Long-term shifts in macroinvertebrate communities have also been observed in European lakes where temperatures have increased (Burgmer et al., 2007), noting that warming may increase species richness in smaller temperate water bodies, especially those at high altitude (Rosset et al., 2010). Although less studied, it has been proposed that tropical ectothermic ("cold blooded") organisms will be particularly vulnerable because they will approach critical maximum temperatures proportionately faster than species in high-latitude environments, despite lower rates of warming (Deutsch et al., 2008; Hamilton, 2010; Laurance et al., 2011).

There is growing evidence that climate-induced changes in precipitation will significantly alter ecologically important attributes of hydrologic regimes in rivers and wetlands, and exacerbate impacts from human water use in developed river basins (*high confidence* in detection, *medium confidence* in attribution; see Box CC-RF; Xenopoulos et al., 2005; Aldous et al., 2011). Freshwater ecosystems in Mediterranean-montane ecoregions (e.g., Australia, California, and South Africa) are projected to experience a shortened wet season and prolonged, warmer summer season (Klausmeyer and Shaw, 2009), increasing the vulnerability of fish communities to drought (Magalhães et al., 2007; Hermoso and Clavero, 2011) and floods (Meyers et al., 2010). Shifts in hydrologic regimes in snowmelt systems, including earlier runoff and declining base flows in summer (Stewart et al., 2005; Stewart, 2009), are projected to alter freshwater ecosystems, through changes in physical habitat and water quality (Bryant, 2009). Declining rainfall and increased interannual variability will most likely increase low-flow and dry-spell duration in dryland regions, leading to reduced water quality in remnant pools (Dahm et al., 2003), reduction in floodplain egg and seed banks (Capon, 2007; Jenkins and Boulton, 2007), the loss of permanent aquatic refugia for fully aquatic species and water birds (Johnson et al., 2005; Bond et al., 2008; Sheldon et al., 2010), altered freshwater food webs (Ledger et al., 2013), and drying out of wetlands (Davis, J.L. et al., 2010).

Climate-induced changes in precipitation will probably be an important factor altering peatland vegetation in temperate and boreal regions, with decreasing wetness during the growing season generally associated with a shift from a Sphagnum dominated to vascular plant dominated vegetation type and a general decline of carbon sequestration in the long term (Limpens et al., 2008). Mire ecosystems (i.e., bogs, transition bogs, and fens) in central Europe face severe climate-induced risk, with increased summer temperatures being particularly important (Essl et al., 2012). Decreased dry season precipitation and longer dry seasons in major tropical peatland areas in Southeast Asia are projected to result in lower water tables more often and for longer periods, with an increased risk of fire (Li et al., 2007; Rieley et al., 2008; Frolking et al., 2011).

Peatlands contain large stocks of carbon that are vulnerable to change through land use and climate change. Although peatlands cover only about 3% of the land surface, they hold the equivalent of half of the atmosphere's carbon (as CO_2), or one-third of the world's soil carbon stock (400 to 600 Pg) (Limpens et al., 2008; Frolking et al., 2011; Page et al., 2011). About 14 to 20% of the world's peatlands are currently used for agriculture (Oleszczuk et al., 2008) and many, particularly peat swamp forests in Southeast Asia, are undergoing rapid major transformations through drainage and burning in preparation for oil palm and other crops or through unintentional burning (Limpens et al., 2008; Hooijer et al., 2010). Deforestation, drainage, and burning in Indonesian peat swamp forests can release 59.4 ± 10.2 Mg CO_2 ha^{-1} yr^{-1} over 25 years (Murdiyarso et al., 2010), contributing significantly to global GHG emissions, especially during periods of intense drought associated with ENSO when burning is more common (Page et al., 2002). Anthropogenic disturbance has changed peatlands from being a weak global carbon sink to a source (Frolking et al., 2011), though interannual variability is large. Fluvial export can also be a significant contributor to carbon losses that has been largely overlooked to date, with recent estimates of DOC export from degraded tropical peatlands 50% higher than in intact systems (Moore et al., 2013). Conserving

peatland areas not yet developed for biofuels or other crops, or rewetting and restoring degraded peatlands to preserve their carbon store, are potential mitigation strategies.

Sea level rise will lead to direct losses of coastal wetlands with associated impacts on water birds and other wildlife species dependent on fresh water (BMT WBM, 2010; Pearlstine et al., 2010; Traill et al., 2010), but the impact will probably be relatively small compared with the degree of direct and indirect human-induced destruction (Nicholls, 2004). River deltas and associated wetlands are particularly vulnerable to rising sea level, and this threat is further compounded by trapping of sediment in reservoirs upstream and subsidence from removal of oil, gas, and water (Syvitski et al., 2009; see Section 5.4.2.7). Lower river flows might exacerbate the impact of sea level rise and thus salinization on freshwater ecosystems close to the ocean (Ficke et al., 2007).

4.3.3.4. Tundra, Alpine, and Permafrost Systems

The High Arctic region, with tundra-dominated landscapes, has warmed more than the global average over the last century (Kaufman et al., 2009; see WGI AR5 Chapter 2). Changes consistent with warming are evident in the freshwater and terrestrial ecosystems and permafrost of the region (Hinzman et al., 2005; Axford et al., 2009; Jia, G.J. et al., 2009; Post et al., 2009; Prowse and Brown, 2010; Romanovsky et al., 2010; Walker et al., 2012). Most of the Arctic has experienced recent change in vegetation photosynthetic capacity, particularly adjacent to rapidly retreating sea ice (Bhatt et al., 2010). Changes in terrestrial environments in Antarctica have also been reported. Vieira et al. (2010) show that in in the Maritime Antarctic permafrost temperatures are close to thaw. Permafrost warming has been observed in continental Antarctica (Guglielmin and Cannone, 2012) and for the Palmer archipelago (Bockheim et al., 2013).

Continued warming is projected to cause the terrestrial vegetation and lake systems of the Arctic to change substantially (*high confidence*). Continued expansion in woody vegetation cover in tundra regions over the 21st century is projected by the CMIP5 ESMs (Bosio et al., 2012; see WGI AR5 Chapter 6), by dynamic global vegetation models driven by other climate model projections, and by observationally based statistical models (Pearson et al., 2013). Changes may be complex (see Box 4-4) and in some cases involve nonlinear and threshold responses to warming and other climatic change (Hinzman et al., 2005; Mueller, D.R. et al., 2009; Bonfils et al., 2012). Arctic vegetation change is expected to continue long after any stabilization of global mean temperature (see WGI AR5 Chapter 6; Falloon et al., 2012). In some regions, reduced surface albedo due to increased vegetation cover is projected to cause further local warming even in scenarios of stabilized GHG concentrations (Falloon et al., 2012).

In the Arctic tundra biome (in contrast to the boreal forests discussed in Section 4.3.3.1.1), vegetation productivity has systematically increased over the past few decades in both North America and northern Eurasia (Goetz et al., 2007; Stow et al., 2007; Jia, G.J. et al., 2009; de Jong et al., 2011; Myers-Smith et al., 2011; Elmendorf et al., 2012). This phenomenon is amplified by retreat of coastal sea ice (Bhatt et al., 2010) and has been widely discussed in the context of increased shrub growth and expansion over the last half century (Forbes et al., 2010; Myers-Smith et al., 2011). Deciduous shrubs and graminoids respond to warming with increased growth (Walker, 2006; Epstein et al., 2008; Euskirchen et al., 2009; Lantz et al., 2010). Analyses of satellite time series data show the increased productivity trend is not unique to shrub-dominated tundra areas (Jia, G.J. et al., 2009; Beck and Goetz, 2011); thus greening is a response shared by multiple vegetation communities and continued changes in the tundra biome can be expected irrespective of shrub presence. The very large spatial scale over which these changes are occurring, the strong warming signal over much of the Arctic for the last 5 decades (Burrows et al., 2011), and the absence of strong confounding factors means that detection of these changes in Arctic systems and their attribution to global warming can be made with *high confidence*, despite the relatively short time frame of most observations (Figure 4-4).

Shrub expansion and height changes are particularly important because they trap snow, mediate winter soil temperature and summer moisture regimes, increase nutrient mineralization, and produce a positive feedback for additional shrub growth (Sturm et al., 2005; Lawrence et al., 2007; Bonfils et al., 2012). Although increased shrub cover and height produce shadowing that reduce ground heat flux and active layer depth, they also reduce surface albedo, increase energy absorption and evapotranspiration (Chapin III et al., 2005; Blok et al., 2010), and produce feedbacks that reinforce shrub densification and regional warming (Lawrence and Swenson, 2011; Bonfils et al., 2012). On balance, these feedbacks can act to partially offset one another, but when coupled with warmer and wetter conditions they act to increase active layer depth and permafrost thaw (Yi et al., 2007; Bonfils et al., 2012).

The Arctic tundra biome is experiencing increasing fire disturbance and permafrost degradation. Both of these processes facilitate conditions for woody species establishment in tundra areas, either through incremental migration or via more rapid long-distance dispersal to areas reinitialized by burning (Epstein et al., 2007; Goetz et al., 2011). When already present at the boreal-tundra ecotone, shrub and tree species show increased productivity with warmer conditions (Devi et al., 2008; Andreu-Hayles et al., 2011; Elmendorf et al., 2012). Tundra fires not only emit large quantities of combusted carbon formerly stored in vegetation and organic soils (Mack et al., 2011; Rocha and Shaver, 2011), but also increase active layer depth during summer months (Racine et al., 2004; Liljedahl et al., 2007; Jorgenson et al., 2010), produce landforms associated with thawing of ice-rich permafrost, and can create conditions that alter vegetation succession (Racine et al., 2004; Lantz et al., 2009; Higuera et al., 2011).

It is *virtually certain* that the area of NH permafrost will continue to decline over the first half of the 21st century (see WGI AR5 Chapter 12) in all RCP scenarios (Figure 4-9; Caesar et al., 2013; Koven et al., 2013). In the RCP2.6 scenario of an early stabilization of CO_2 concentrations, the permafrost area is projected to stabilize at a level approximately 20% below the 20th century area, and then begin a slight recovering trend. In RCP4.5, in which CO_2 concentration is stabilized at approximately 550 ppmv by the mid-21st century, the simulations that extend beyond 2100 show permafrost continuing to decline for at least another 250 years. In the RCP8.5 scenario of ongoing CO_2 rise, the permafrost area is simulated to approach zero by the middle of the 22nd century in

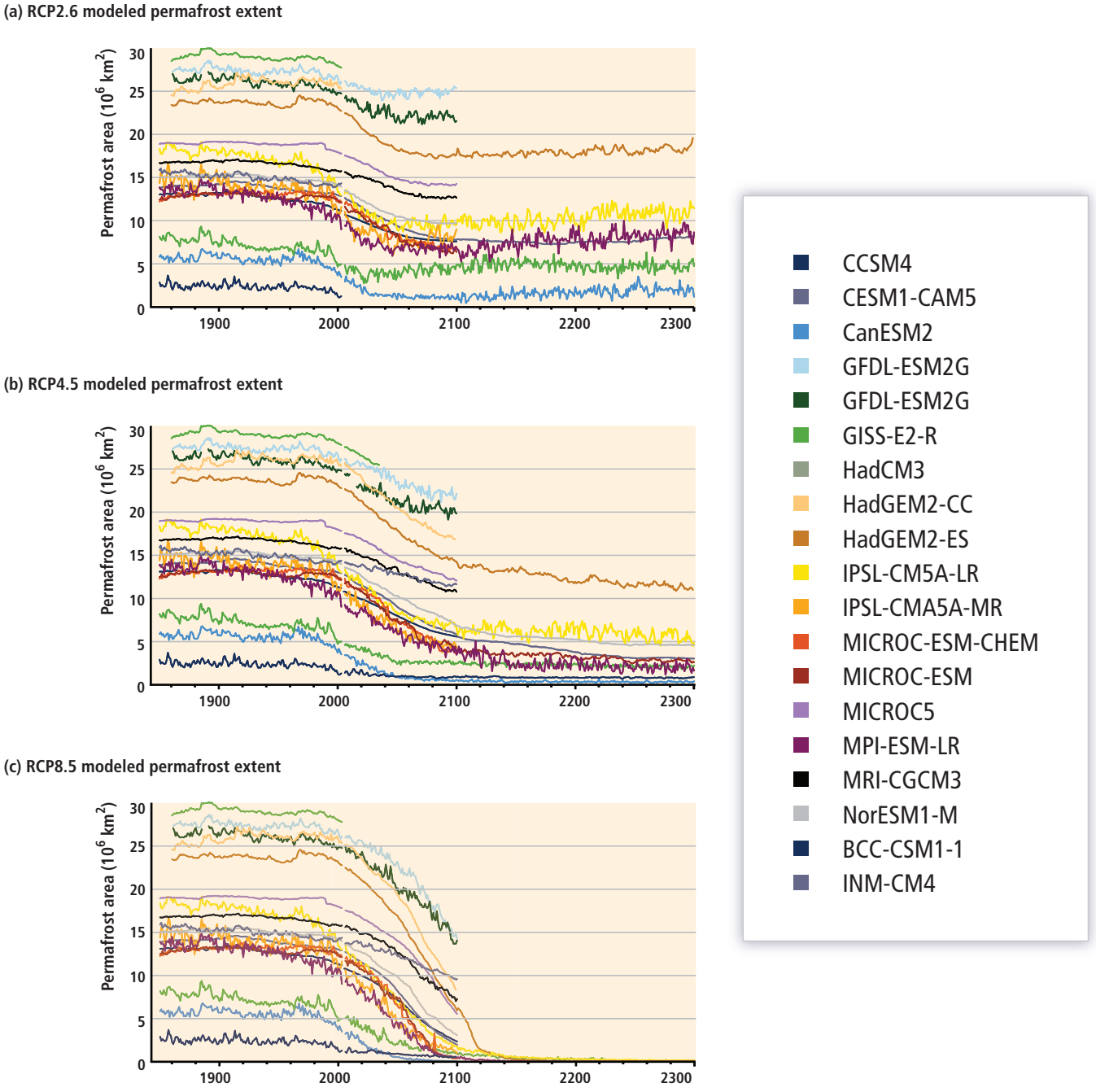

Figure 4-9 | CMIP5 multi-model simulated area of Northern Hemisphere permafrost in the upper 3 m of soil, from 1850 to 2100 or 2300 depending on extent of individual simulations. Each panel shows historical (1850–2005) and projected (2005–2100 or 2300) simulations for (a) Representative Concentration Pathway 2.6 (RCP2.6), (b) RCP4.5, and (c) RCP8.5. The observed current permafrost extent is 15 × 10^6 km^2. (Based on Koven et al., 2013, with analysis extended to 2300 following Caesar et al., 2013).

simulations that extend beyond 2100. RCP8.5 simulations that ended at 2100 showed continued permafrost decline in the late 21st century, although at slower rates in some cases as the remaining permafrost area decreases (Figure 4-9.).

Frozen soils and permafrost currently hold about 1700 PgC, more than twice the carbon than the atmosphere, and thus represent a particularly large vulnerability to climate change (i.e., warming) (see WGI AR5 Chapter 6). Although the Arctic is currently a net carbon sink, continued warming will act to turn the Arctic to a net carbon source, which will in turn create a potentially strong positive feedback to accelerate Arctic (and global) warming with additional releases of CO_2, CH_4, and perhaps N_2O, from the terrestrial biosphere into the atmosphere (*high confidence*; Schuur et al., 2008, 2009; Maslin et al., 2010; McGuire et al., 2010; O'Connor et al., 2010; Schaefer et al., 2011; see WGI AR5 Chapter 6 for detailed treatment of biogeochemistry, including feedbacks). Moreover, this feedback is already accelerating due to climate-induced increases in fire (McGuire et al., 2010; O'Donnell et al., 2011). The rapid retreat of snow cover and resulting spread of shrubs and trees into areas currently dominated by tundra has begun, and will continue to serve

Box 4-4 | Boreal-Tundra Biome Shift

Changes in a suite of ecological processes currently underway across the broader Arctic region are consistent with Earth System Model (ESM) predictions of climate-induced geographic shifts in the range extent and functioning of the tundra and boreal forest biomes (Figure 4-10). Until now, these changes have been gradual shifts across temperature and moisture gradients, rather than abrupt. Responses are expressed through gross and net primary production, microbial respiration, fire and insect disturbance, vegetation composition, species range expansion and contraction, surface energy balance and hydrology, active layer depth and permafrost thaw, and a range of other inter-related variables. Because the high northern latitudes are warming more rapidly than other parts of the Earth, due at least in part to Arctic amplification (Serreze and Francis, 2006), the rate of change in these ecological processes are sufficiently rapid that they can be documented *in situ* (Hinzman et al., 2005; Post et al., 2009; Peng et al., 2011; Elmendorf et al., 2012) as well as from satellite observations (Goetz et al., 2007; Beck, P.S.A. et al., 2011; Xu et al., 2013) and captured in ESMs (McGuire et al., 2010).

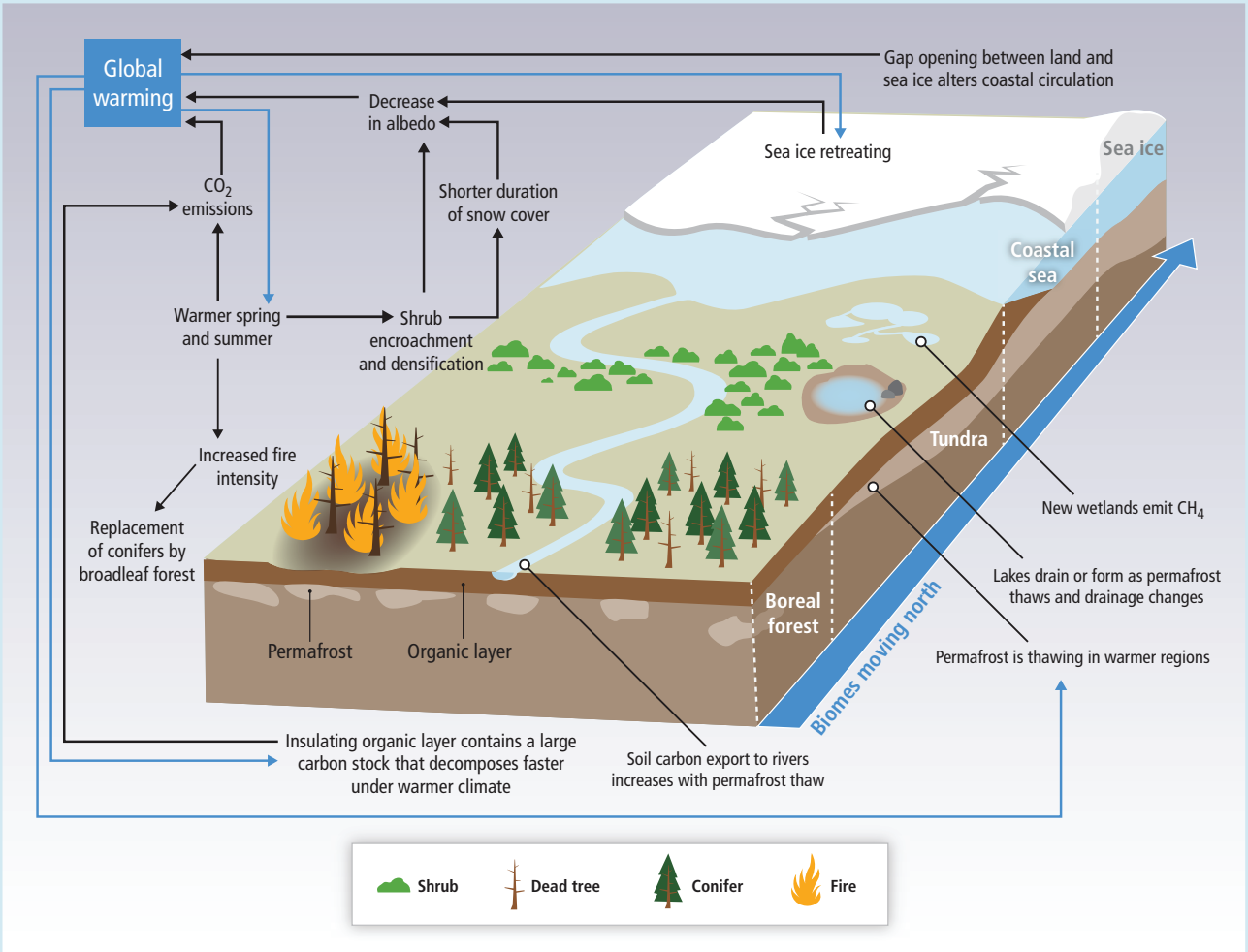

Figure 4-10 | Tundra–boreal biome shift. Earth System Models predict a northward shift of Arctic vegetation with climate warming, as the boreal biome migrates into what is currently tundra. Observations of shrub expansion in tundra, increased tree growth at the tundra–forest transition, and tree mortality at the southern extent of the boreal forest in recent decades are consistent with model projections. Vegetation changes associated with a biome shift, which is facilitated by intensification of the fire regime, will modify surface energy budgets, and net ecosystem carbon balance, permafrost thawing, and methane emissions, with net feedbacks to additional climate change.

Continued next page →

Box 4-4 (continued)

Gradual changes in composition resulting from decreased evergreen conifer productivity and increased mortality, as well as increased deciduous species productivity, can be facilitated by more rapid shifts associated with fire disturbance where it can occur (Mack et al., 2008; Johnstone et al., 2010; Roland et al., 2013). Each of these interacting processes, as well as insect disturbance and associated tree mortality, are tightly coupled with warming-induced drought (Choat et al., 2012; Ma et al., 2012; Anderegg et al., 2013a). Similarly, gradual productivity increases at the boreal-tundra ecotone are facilitated by long distance dispersal into areas disturbed by tundra fire and thermokarsting (Tchebakova et al., 2009; Brown, 2010; Hampe, 2011). In North America these coupled interactions set the stage for changes in ecological processes, already documented, consistent with a biome shift characterized by increased deciduous composition in the interior boreal forest and evergreen conifer migration into tundra areas that are, at the same time, experiencing increased shrub densification. The net feedback of these ecological changes to climate is multi-faceted, complex, and not yet well known across large regions except via modeling studies, which are often poorly constrained by observations.

as a positive feedback accelerating high-latitude warming (Chapin III et al., 2005; Bonfils et al., 2012).

There is *medium confidence* that rapid change in the Arctic is affecting its animals. For example, seven of 19 sub-populations of the polar bear are declining in number, while four are stable, one is increasing, and the remaining seven have insufficient data to identify a trend (Vongraven and Richardson, 2011). Declines of two of the sub-populations are linked to reductions in sea ice (Vongraven and Richardson, 2011). Polar bear populations are projected to decline greatly in response to continued Arctic warming (Hunter et al., 2010; Stirling and Derocher, 2012), and it is expected that the populations of other Arctic animals will be affected dramatically by climate change, often in complex but potentially dramatic ways (e.g., Post et al., 2009; Sharma et al., 2009; Gallant et al., 2012; Gilg et al., 2012; Post and Brodie, 2012; Gauthier et al., 2013; Nielsen and Wall, 2013; Prost et al., 2013; White et al., 2013). Simple niche-based or climatic envelope models have difficulty in capturing the full complexity of these future changes (MacDonald, 2010).

There is *high confidence* that alpine systems are already showing a high sensitivity to ongoing climate change and will be highly vulnerable to change in the future. In western North America, warming, glacier retreat, snowpack decline, and drying of soils are already causing a large increase in mountain forest mortality and wildfire, plus other ecosystem impacts (e.g., Westerling et al., 2006; Crimmins et al., 2009; van Mantgem et al., 2009; Pederson et al., 2010; Muhlfeld et al., 2011; Brusca et al., 2013; Williams et al., 2013), and disturbance will continue to be an important agent of climate-induced change in this region (Littell et al., 2010). Globally, tree line altitude appears to be changing, although not always in simple ways (Harsch et al., 2009; Tingley et al., 2012) and may sometimes be due to factors not related to climate change. Responses to climate change in high-altitude ecosystems are taking place in Africa, Asia, Europe, and elsewhere (Cannone et al., 2007, 2008; Yasuda et al., 2007; Lenoir et al., 2008, 2010; Britton et al., 2009; Chen et al., 2009, 2011; Cui and Graf, 2009; Normand et al., 2009; Allen, C.D. et al., 2010; Eggermont et al., 2010; Engler et al., 2011; Kudo et al., 2011; Laurance et al., 2011; Dullinger et al., 2012). For example, in a study of permanent plots from 1994 to 2004 in the Austrian high Alps, a range contraction of subnival to nival plant species was indicated at the downslope edge, and an expansion of alpine pioneer species at the upslope edge (Pauli et al., 2007). Thermophilous vascular plant species were observed to colonize in alpine mountain-top vegetation across Europe during the past decade (Gottfried et al., 2012). As with the Arctic, permafrost thawing in alpine systems could provide a strong positive feedback (e.g., Tibet; Cui and Graf, 2009).

4.3.3.5. Highly Human-Modified Systems

About a quarter of the land surface is now occupied by ecosystems highly modified by human activities. In this section we assess the vulnerability to climate change only of those modified systems not dealt with elsewhere, that is, excluding agriculture (Chapter 7), freshwater fisheries (Chapter 3), and urban areas (Chapter 8).

4.3.3.5.1. Plantation forestry

Plantation forests are established through afforestation or reforestation, often with tree crop replacement (Dohrenbusch and Bolte, 2007; FAO, 2010). They differ from natural or semi-natural forests (Section 4.3.3.1) by generally being even-aged, having a reduced species diversity (sometimes of non-native species), and being dedicated to the production of timber, pulp, and/or bioenergy. Plantation forests contribute 7% to the global forest area (FAO, 2010), an increase of 5 million hectares between 2000 and 2010 (FAO, 2010). Most recent plantations have been established by afforestation of non-forest areas in the tropics and subtropics and some temperate regions, particularly China (Kirilenko and Sedjo, 2007; FAO, 2010). Afforestation usually results in net CO_2 uptake from the atmosphere (Canadell and Raupach, 2008; Van Minnen et al., 2008) but does not necessarily result in a reduction in global warming (Bala et al., 2007; see Section 4.3.4.5).

Growth rates in plantation forests have generally increased during the last decades but the variability is large. In forests that are not highly

water limited, increased growth is consistent with higher temperatures and extended growing seasons. As in the case of forests in general, clear attribution is difficult because of the interaction of multiple environmental drivers as well as changes in forest management (e.g., Boisvenue and Running, 2006; Ciais et al., 2008; Dale et al., 2010; see also Section 4.3.3.1). In Europe much of the increase has been attributed to recovery following previously more intense harvesting (Ciais et al., 2008; Lindner et al., 2010).

Several studies using forest yield models suggest future increases in forest production (Kirilenko and Sedjo, 2007). These results may overestimate the positive effects of elevated CO_2 (Kirilenko and Sedjo, 2007; see Section 4.2.4.4). The effects of disturbances such as wildfires, forest pests, pathogens, and windstorms, which are major drivers of forest dynamics, are poorly represented in the models (Loustau, 2010; see also Section 4.3.3.1 and Box 4-2). The results from different models often differ substantially both regarding forest productivity (e.g., Sitch et al., 2008; Keenan et al., 2011) and potential species ranges (see Section 4.3.3.1.2). Decreased forest production is expected in already dry forest regions for which further drying is projected, such as the southwestern USA (Williams, A.P. et al., 2010). Extreme drying may also decrease yields in forests currently not water limited (e.g., Sitch et al., 2008; see Section 4.3.3.1). Plantations in cold-limited areas could benefit from global warming, provided that increased fires, storms, pests, and pathogens do not outweigh the potential direct climate effects on tree growth rates.

Low species diversity (and low genetic diversity within species where clones or selected provenances are used) renders plantation forests less resilient to climate change than natural forests (e.g., Hemery, 2008). Choosing provenances that are well adapted to current climates but pre-adapted to future climates is difficult because of uncertainties in climate projections at the time scale of a plantation forest rotation (Broadmeadow et al., 2005). How forest pests and pathogens will spread as a result of climate change and other factors is highly uncertain. New pathogen-tree interactions may arise (e.g., Brasier and Webber, 2010). Adaptive management can decrease the vulnerability of plantation forests to climate change (Hemery, 2008; Bolte et al., 2009; Seppälä, 2009; Dale et al., 2010). For example, risk spreading by promoting mixed stands, containing multiple species or provenances, combined with natural regeneration (Kramer et al., 2010), has been advocated as an adaptation strategy for temperate forests (Hemery, 2008; Bolte et al., 2010) and tropical forests (Erskine et al., 2006; Petit and Montagnini, 2006). Incomplete knowledge of the ecology of tropical tree species and little experience in managing mixed tropical tree plantations remains a problem (Hall et al., 2011). Especially at the equator-ward limits of cold-adapted species, such as Norway spruce (*Picea abies*) in Europe, climate change will *very likely* lead to a shift in the main tree species used for forest plantations (Iverson et al., 2008; Bolte et al., 2010).

4.3.3.5.2. Bioenergy systems

The production of modern bioenergy is growing rapidly throughout the world in response to climate mitigation and energy security policies (Kirilenko and Sedjo, 2007). WGIII AR5 Chapter 7 addresses the potential of bioenergy as a climate mitigation strategy. The vulnerability of bioenergy systems to climate change is similar to that of plantation forestry (Section 4.3.3.5.1) or food crops (Section 7.3): in summary, they remain viable in the future in most but not all locations, but their viability is increasingly uncertain for high levels of climate change (Haberl et al., 2011). Oliver, R.J. et al. (2009) suggested that rising CO_2 might contribute to increased drought tolerance in bioenergy crops (because it leads to improved plant water use efficiency).

The unintended consequences of large-scale land use changes driven by increasing bioenergy demand are addressed in Section 4.4.4.

4.3.3.5.3. Cultural landscapes

Cultural landscapes are characterized by a long history of human-nature interactions, which results in a particular configuration of species and landscape pattern attaining high cultural significance (Rössler, 2006). Examples are grassland or mixed agriculture landscapes in Europe, rice landscapes in Asia (Kuldna et al., 2009), and many others across the globe (e.g., Rössler, 2006; Heckenberger et al., 2007). Such landscapes are often agricultural, but we deal with them here because their perceived value is only partly in terms of their agricultural products.

It has been suggested that protected area networks (such as Natura 2000 in Europe, which includes many cultural landscape elements) be adjusted to take into account climate change (Bertzky et al., 2010). Conserving species in cultural landscapes (e.g., EU Council, 1992) generally depends on maintaining certain types of land use. Doing so under climate change requires profound knowledge of the systems and species involved, and conservation success so far has been limited (see Thomas et al., 2009, for a notable exception). Understanding the relative importance of climate change and land management change is critical (Settele and Kühn, 2009). To date land use changes have been the most obvious driver of change (Nowicki et al., 2007); impacts have been attributed to climate change (with *low* to *medium confidence*) in only a few examples (Devictor et al., 2012). Even in these, combined land use-climate effects explain the pattern of observed threats better than either alone (Schweiger et al., 2008, 2012; Clavero et al., 2011).

There is *very high confidence* that species composition and landscape structure are changing in cultural landscapes such as Satoyama landscapes in Japan or mixed forest, agricultural landscapes in Europe. Models and experiments suggest that climate change should be contributing to these observed changes. The land use and land management signal is so strong in these landscapes that there is *very low confidence* that we can attribute these observations to climate change (Figure 4-4).

4.3.3.5.4. Urban ecosystems

Although urban areas (for definition see Section 8.1.2) cover only 0.5% of the Earth's land surface (Schneider et al., 2009), more than half of humanity lives there (increasing annually by 74 million people; UN DESA Population Division, 2012) and they harbor a large variety of species (McKinney, 2008). The frequency and magnitude of warm days and nights (heat waves) is *virtually certain* to increase globally in the future

Frequently Asked Questions

FAQ 4.5 | Why does it matter if ecosystems are altered by climate change?

Ecosystems provide essential services for all life: food, life-supporting atmospheric conditions, drinkable water, as well as raw materials for basic human needs such as clothing and housing. Ecosystems play a critical role in limiting the spread of human and non-human diseases. They have a strong impact on the weather and climate itself, which in turn impacts agriculture, food supplies, socioeconomic conditions, floods, and physical infrastructure. When ecosystems change, their capacity to supply these services changes as well—for better or worse. Human well-being is put at risk, along with the welfare of millions of other species. People have a strong emotional, spiritual, and ethical attachment to the ecosystems they know, and the species they contain.

By "ecosystem change" we mean changes in some or all of the following: the number and types of organisms present; the ecosystem's physical appearance (e.g., tall or short, open or dense vegetation); and the functioning of the system and all its interactive parts, including the cycling of nutrients and productivity. Though in the long term not all ecosystem changes are detrimental to all people or to all species, the faster and further ecosystems change in response to new climatic conditions, the more challenging it is for humans and other species to adapt to the new conditions.

(IPCC, 2012); this trend is higher in urban than in rural areas (McCarthy et al., 2010). Heavy rainfall events are also projected to increase (IPCC, 2012), and although the hydrological conditions in urban areas make them prone to flooding (*medium confidence*), there is *limited evidence* that they will be over-proportionally affected. It is very likely that sea level rise in the future will contribute to flooding, erosion, and salinization of coastal urban ecosystems (IPCC, 2012). Climate change is projected to increase the frequency of landslides (UN-HABITAT, 2011). Climate change impacts on urban ecosystems and biodiversity have received comparatively little attention, with water availability being an exception (Hunt and Watkiss, 2011). Changes in water availability and quality due to changes in precipitation, evaporation, or in salinity regimes will especially affect urban freshwater ecosystems (Hunt and Watkiss, 2011). As in other ecosystems, climate change will lead to a change in species composition, the frequency of traits, and ecosystem services from urban ecosystems. Knapp, S. et al. (2008) found that trait composition of plant communities changes during urbanization toward adaptive characteristics of dry and warm environments (see also Sections 4.2.4.6 and 4.3.2.5). Urban areas are one of the main points of introduction of alien species (e.g., for plants through urban gardening; Knapp, S. et al., 2012). Increased damage by phytophagous insects to plants in urban environments is anticipated (Kollár et al., 2009; Lopez-Vaamonde et al., 2010; Tubby and Webber, 2010; see also Section 8.2.4.5).

4.3.4. Impacts on Key Ecosystem Services

Ecosystem services are the benefits that people derive from ecosystems (see Glossary). Many ecosystem services are plausibly vulnerable to climate change. The Millennium Ecosystem Assessment classification (Millennium Ecosystem Assessment, 2003) recognizes *provisioning services* such as food (Chapter 7), fiber (Section 4.3.4.2), bioenergy (Section 4.3.4.3), and water (Chapter 3); *regulating services* such as climate regulation (Section 4.3.4.5), pollination, pest and disease control (Section 4.3.4.4), and flood control (Chapter 3); *supporting services* such as primary production (Section 4.3.2.2) and nutrient cycling (Section 4.2.4.2, and indirectly Section 4.3.2.3); and *cultural services*, including recreation and aesthetic and spiritual benefits (Section 10.6). Section 4.3.4.1 focuses on ecosystem services not already covered in the sections referenced above.

4.3.4.1. Habitat for Biodiversity

Climate change can alter habitat for species by inducing (1) shifts in habitat distribution that are not followed by species, (2) shifts in species distributions that move them outside of their preferred habitats, and (3) changes in habitat quality (Dullinger et al., 2012; Urban et al., 2012). Climate change impacts on habitats for biodiversity are already occurring (see the polar bear example in Section 28.2.2.1.3) but are not yet a widespread phenomenon. Models of future climate change-induced shifts in the distribution of ecosystems suggest that many species could be outside of their preferred habitats within the next few decades (Urban et al., 2012; see Sections 4.3.2.5, 4.3.3, and Figure 4-1).

Hole et al. (2009) report that the majority of African birds would have to move large distances (up to several hundred kilometers) over the next 60 years (under SRES B2a), resulting in substantial turnover of species within protected areas (>50% turnover in more than 40% of Important Bird Areas of Africa). To reach suitable climates they will have to migrate across unfavorable habitats. Many may continue to find suitable climate within the protected area network, but will be forced to cope with new habitat constraints (Hole et al., 2009). Araujo et al. (2011) estimate that by 2080 approximately 60% (58 ± 2.6%) of plants and vertebrate species will no longer have favorable climates within European protected areas, often pushing them into unsuitable or less preferred habitats (based on SRES A1, A2, B1, and A1FI scenarios). Wiens et al. (2011) project similar effects in the western USA (until the year 2069, based on SRES A2 scenarios), but also find that climate change may open up new opportunities for protecting species in areas where

climate is currently unsuitable. In some cases climate change may allow species to move into areas of lower current or future land use pressure including protected areas (Bomhard et al., 2005). These studies strongly argue for a rethinking of protected areas networks and of the importance of the habitat matrix outside of protected areas as a key to migration and long-term survival of species (see Sections 4.4.2.2, 4.4.2.3).

In the long term, some habitat types may disappear entirely due to climate change (see Section 4.3.3 and Figure 4-1). Climates are projected to occur in the future that at least in some features do not represent climates that existed in the past (Williams, J.W. et al., 2007; Wiens et al., 2011), and in the past climate shifts have resulted in vegetation types that have no current analog (Section 4.2.3). The impacts of habitat change on species abundance and extinction risk are difficult to evaluate because at least some species are able to adapt to novel habitats (Prugh et al., 2008; Oliver, T. et al., 2009). The uncertainty in habitat specificity is one reason why quantitative projection of changes in extinction rates is difficult (Malcolm et al., 2006).

The effects of climate change on habitat quality are less well studied than shifts in species or habitat distributions. Several recent studies indicate that climate change may have altered habitat quality already and will continue to do so (Iverson et al., 2011; Matthews et al., 2011). For example, decreasing snowfall in the southwestern USA has negatively affected the habitat for songbirds (Martin and Maron, 2012).

4.3.4.2. Timber and Pulp Production

In most areas with forest plantations, forest growth rates have increased during the last decades, but the variability is large, and in some areas production has decreased (see Section 4.3.3.1). In forests that are not highly water limited, these trends are consistent with higher temperatures and extended growing seasons, but, as in the case of forests in general, clear attribution is difficult because many environmental drivers and changes in forest management interact (e.g., Boisvenue and Running, 2006; Ciais et al., 2008; Dale et al., 2010; see also Section 4.3.3.1). In Europe a reduction in harvesting intensity has contributed (Ciais et al., 2008; Lindner et al., 2010).

Forest yield models project future increases in forest production under climate change, perhaps over optimistically (Kirilenko and Sedjo, 2007; see Section 4.2.4.4). Using a model that accounts for fire effects and insect damage, Kurz et al. (2008) showed that the Canadian forest sector may have transitioned from a sink to a source of carbon.

4.3.4.3. Biomass-Derived Energy

Bioenergy sources include traditional forms such as wood and charcoal from forests (see Section 4.3.3.1) and more modern forms such as the industrial burning of biomass wastes, the production of ethanol and biodiesel, and plantations of bioenergy crops. While traditional biofuels have been in general decline as users switch to fossil fuels or electricity, they remain dominant energy sources in many less developed parts of the world, such as Africa, and retain a niche in developed countries. Generally, potentials of bioenergy production under climate change may be high, but are very uncertain (Haberl et al., 2011).

4.3.4.4. Pollination, Pest, and Disease Regulation

It can be inferred that global change will result in new communities (Gilman et al., 2010; Schweiger et al., 2010). As these will have had little opportunity for coevolution, changes in ecological interactions, such as shifts in herbivore diets, the range of prey of predators, or in pollination networks are to be expected (Tylianakis et al., 2008; Schweiger et al., 2012). This may result in temporarily reduced effectiveness of the "regulating services," which generally depend on species interactions (Montoya and Raffaelli, 2010). Burkle et al. (2013) show that the loss of species reduces co-occurrence of interacting species and thus reduces ecosystem functions based on them.

Climate change tends to increase the abundance of pest species, particularly in previously cooler climates, but assessments of changes in impacts are hard to make (Payette, 2007). Insect pests are directly influenced by climate change, for example, through a longer warm season during which to breed, and indirectly, for example, through the quality of food plants (Jamieson et al., 2012) or via changes in their natural enemies (predators and parasitoids). Insects have well-defined temperature optima; warming toward the optimum leads to increased vitality and reproduction (Allen, C.D. et al., 2010). Mild winters in temperate areas promote pests formerly controlled by frost sensitivity. For the vast majority of indirect effects, information is scarce. Further assessments of climate change effects on pest and disease dynamics are found in Sections 7.3.2.3 for agricultural pests and 11.5.1 for human diseases.

Climate change has severe negative impacts on pollinators (including honeybees) and pollination (Kjøhl et al., 2011) (*medium confidence*). After land use changes, climate change is regarded as the second most relevant factor responsible for the decline of pollinators (Potts et al., 2010; for other factors see Biesmeijer et al., 2006; Brittain et al., 2010a,b). The potential influence of climate change on pollination can be manifold (compare Hegland et al., 2009; Schweiger et al., 2010; Roberts et al., 2011). There are a few observational studies, which mostly relate to the phenological decoupling of plants and their pollinators (Gordo and Sanz, 2005; Bartomeus et al., 2011). While Willmer (2012) states, based on experimental studies, that phenological effects may be less important than has been suggested, an analysis of phenological observations in plants by Wolkovich et al. (2012) shows that experimental data on phenology may grossly underestimate the actual phenological shifts.

Le Conte and Navajas (2008) state that the generally observed decline in honeybees is a clear indication of an increasing susceptibility to global change phenomena, with pesticide application, new diseases, and stress (and a combination of these) as the most relevant causes. Climate change may contribute by modifying the balance between honeybees and their environment (including exposure or susceptibility to diseases). Honeybees show a high capacity to adjust to a variety of environments; their high genetic diversity should allow them to also cope with climatic change (Bartomeus et al., 2011). The preservation of

genetic variability within honeybees is regarded as a key adaptation strategy for pollination services (Le Conte and Navajas, 2008).

4.3.4.5. Moderation of Climate Change, Variability, and Extremes

The focus of this section is on processes operating at regional to global scales, rather than the well-known microclimatic benefits of ecosystems in smoothing day-night temperature variations and providing local evaporative cooling. In the decade 2000–2009, the global net uptake of CO_2 by terrestrial ecosystems was a large fraction of the anthropogenic CO_2 emissions to the atmosphere from all sources, reducing the rate of climate change proportionately (Section 4.3.2.3; WGI AR5 Section 6.3.2).

Afforestation or reforestation are potential climate mitigation options (Van Minnen et al., 2008; Vaughan and Lenton, 2011; Fiorese and Guariso, 2013; Singh et al., 2013) but, as discussed in Section 4.2.4.1, the net effect of afforestation on the global climate is mixed and context dependent. Wickham et al. (2012) found significant positive correlations between the average annual surface temperature and the proportion of forest in the landscape and conclude that the climate benefit of temperate afforestation is unclear. Where low-albedo forest canopies replace higher-albedo surfaces such as soil, grassland, or snow, the resultant increase in net radiative forcing counteracts the benefits of carbon sequestration to some degree (Arora and Montenegro, 2011). Where the cloud cover fraction is low and the albedo difference is large, that is, outside the humid tropics, the long-term net result of afforestation can be global warming (Bala et al., 2007; Bathiany et al., 2010; Schwaiger and Bird, 2010). Accounting for changes in albedo and indirect greenhouse effects are not currently required in the formal rules for quantifying for the climate effects of land use activities (Schwaiger and Bird, 2010; Kirschbaum et al., 2012). There are potential negative trade-offs between afforestation for climate mitigation purposes and other ecosystem services, such as water supply (Jackson et al., 2005) and biodiversity maintenance (CBD, 2012; Russell et al., 2012).

It has been suggested (Ridgwell et al., 2009) that planting large areas of crop varieties with highly reflective leaves could help mitigate global change. Model analyses indicate this "geo-engineering" strategy would be marginally effective at high latitudes, but have undesirable climate consequences at low latitudes. Measurements of leaf albedo in major crops show that the current range of variability is insufficient to make a meaningful difference to the global climate (Doughty et al., 2011).

4.4. Adaptation and Its Limits

4.4.1. Autonomous Adaptation by Ecosystems and Wild Organisms

Autonomous adaptation (see Glossary under adaptation) refers to the adjustments made by ecosystems, including their human components, without external intervention, in response to a changing environment (Smit et al., 2000)—also called "spontaneous adaptation" (Smit et al., 2007). In the context of human systems it is sometimes called "coping capacity." The capacity for autonomous adaptation is part of resilience but is not exactly synonymous (Walker et al., 2004).

All social and ecological systems have some capacity for autonomous adaptation. Ecosystems that have persisted for a long time can reasonably be inferred to have a high capacity for autonomous adaptation, at least with respect to the variability that they have experienced in the past. An environmental change that is more rapid than in the past or is accompanied by other stresses may exceed the previously demonstrated adaptive capacity of the system. Adaptation at one level, for instance by organisms in a community, can confer greater resilience at higher organization levels, such as the ecosystem (Morecroft et al., 2012). The mechanisms of autonomous adaptation of organisms and ecosystems consist of changes in the physiology, behavior, phenology, or physical form of organisms, within the range permitted by their genes and the variety of genes in the population; changes in the genetic composition of the populations; and change in the composition of the community, through in- or out-migration or local extinction.

The ability to project impacts of climate change on ecosystems is complicated by the potential for species to adapt. Adaptation by individual species increases their ability to survive and flourish under different climatic conditions, possibly leading to lower risks of extinction than predicted from statistical correlations between current distribution and climate (Botkin et al., 2007). It may also affect their interactions with other species, leading to disruption of the biotic community (Visser and Both, 2005).

4.4.1.1. Phenological

Changes in phenology are occurring in many species and locations (Section 4.3.2.1). Further evidence since AR4 shows how this can be an adaptation to climate change, but also the limits to phenological adaptation. An organism's phenology is typically highly adapted to the climate seasonality of the environment in which it evolved. Species unable to adjust their phenological behavior will be negatively affected, particularly in highly seasonal habitats (Both et al., 2010).

Moreover, the phenology of any species also needs to be keyed to the phenology of other species with which it interacts, such as competitors, food species, and pollinators. Systematic cross-taxa studies indicate different rates of phenological change for different species and trophic levels (Parmesan, 2007; Cook et al., 2008; Thackeray et al., 2010). If adaptation is insufficiently rapid or coordinated between interdependent species, disruption of ecological features such as trophic cascades, competitive hierarchies, and species coexistence is inferred to result (Nakazawa and Doi, 2012). Lack of coordination can occur if one of the species is cued to environmental signals that are not affected by climate change, such as day length (Parmesan, 2006). Increasing temperatures may bring species either more into or out of synchrony, depending on their respective starting positions (Singer and Parmesan, 2010), although evidence is more toward a loss of synchrony (Thackeray et al., 2010).

Changes in interspecific interactions, such as predator-prey or interspecific competition for food, stemming from changes in phenological characteristics and breakdown in synchrony between species have been observed. For example, bird breeding is most effective when synchronized with the availability of food, so changes in the phenology of food supplies can exert a selective pressure on birds. In a study of 100

European migratory bird species, those that advanced their arrival date showed stable or increasing populations between 1990 and 2000, while those that did not adjust their arrival date on average showed declining populations (Møller et al., 2008). In a comparison of nine Dutch populations of the migratory pied flycatcher (*Ficedula hypoleuca*) between 1987 and 2003, populations declined by 90% in areas where food peaked early in the season and the arrival of the birds was mis-timed, but not in areas with a later food peak that could still be exploited by early breeding birds (Both et al., 2006). However, compensating processes can exist: for example, in a 4-decade study of great tits (*Parus major*), breeding populations were buffered against phenological mismatch due to relaxed competition between individual fledglings (Reed et al., 2013). Between 1970 and 1990, changes in migration date did not predict changes in population sizes (Møller et al., 2008).

Bird breeding can also be affected by phenological shifts in competing species and predators. Between 1953 and 2005 in southwestern Finland, the onset of breeding of the resident great tit *Parus major* and the migratory pied flycatcher (*Ficedula hypoleuca*) became closer to each other, increasing competition between them (Ahola et al., 2007). The edible dormouse (*Glis glis*), a nest predator, advanced its hibernation termination by -8 days per decade in the Czech Republic between 1980 and 2005 due to increasing annual spring air temperatures, leading to increased nest predation in three out of four surveyed bird species (Adamik and Kral, 2008).

Plant-insect interactions have also been observed to change. In Illinois, USA, the pattern of which plants were pollinated by which bees were altered by differing rates of phenological shifts and landscape changes over 120 years, with 50% of bee species becoming locally extinct (Burkle et al., 2013). Increasing asynchrony of the winter moth (*Operophtera brumata*) and its feeding host oak tree (*Quercus robur*) in the Netherlands was linked to increasing spring temperatures but unchanging winter temperatures (van Asch and Visser, 2007). Warmer temperatures shorten the development period of European pine sawfly larvae (*Neodiprion sertifer*), reducing the risk of predation and potentially increasing the risk of insect outbreaks, but interactions with other factors including day length and food quality may complicate this prediction (Kollberg et al., 2013). In North America, the spruce budworm (*Choristaneura fumiferana*) lays eggs with a wide range of emergence timings, so the population as a whole is less sensitive to changing phenology of host trees (Volney and Fleming, 2007).

The environmental cues for phenological events are complex and multi-layered (Körner and Basler, 2010; Singer and Parmesan, 2010). For instance, many late-succession temperate trees require a chilling period in winter, followed by a threshold in day length, and only then are sensitive to temperature. As a result, simple projections of current phenological trends may be misleading, since the relative importance of cues can change (Cook et al., 2012b). The effects are complex and sometimes apparently counterintuitive, such as the increased sensitivity of flowering in high-altitude perennial herbs in the Rocky Mountains to frost because plants begin flowering earlier as a result of earlier snowmelt (Inouye, 2008).

It has been suggested that shorter generation times give greater opportunity for autonomous adaptation through natural selection (Rosenheim and Tabashnik, 1991; Bertaux et al., 2004), but a standardized assessment of 25,532 rates of phenological change for 726 UK taxa indicated that generation time had only limited influence on adaptation rates (Thackeray et al., 2010).

There is *high confidence* (*much evidence*, *medium agreement*) that climate change-induced phenological shifts will continue to alter the interactions between species in regions with a marked seasonal cycle.

4.4.1.2. Evolutionary and Genetic

Since AR4 there has been substantial progress in defining the concepts and tools necessary for documenting and predicting evolutionary and genetic responses to recent and future climate change, often referred to as "rapid evolution." Evolution can occur through many mechanisms, including selection of existing genes or genotypes within populations, hybridization, mutation, and selection of new adaptive genes and perhaps even through epigenetics (Chevin et al., 2010; Chown et al., 2010; Lavergne et al., 2010; Paun et al., 2010; Hoffmann and Sgro, 2011; Anderson et al., 2012a; Donnelly et al., 2012; Franks and Hoffmann, 2012; Hegarty, 2012; Merilä, 2012; Bell, 2013; Zhang et al., 2013). Mechanisms such as selection of existing genes and genotypes, hybridization, and epigenetics can lead to adaptation in very few generations, while others, notably mutation and selection of new genes, typically take many tens of generations. This means that species with very fast life cycles, for example, bacteria, should in general have greater capacity to respond to climate change than species with long life cycles, such as large mammals and trees. There is a paucity of observational or experimental data that can be used for detection and attribution of recent climate effects on evolution.

4.4.1.2.1. Observed evolutionary and genetic responses to rapid changes in climate

There is a small but growing body of observations supporting the AR4 assessment that some species may have adapted to recent climate warming or to climatic extremes through genetic responses (e.g., plants: Franks and Weis, 2008; Hill et al., 2011; Anderson et al., 2012b; vertebrates: Ozgul et al., 2010; Phillimore et al., 2010; Husby et al., 2011; Karell et al., 2011; insects: Buckley et al., 2012; van Asch et al., 2012). Karell et al. (2011) found increasing numbers of brown genotypes of the tawny owl (*Strix aluco*) in Finland over the course of the last 28 years and attributed it to fewer snow-rich winters, which creates strong selection pressure against the white genotype. Earlier spawning by the common frog (*Rana temporaria*) in Britain could be attributed largely to local genetic adaptation to increasing spring temperatures (Phillimore et al., 2010). Using a combination of models and observations, Husby et al. (2011) have built a case for detection and attribution of genetic adaptation in an insectivorous bird and in an herbivorous insect that has tracked warming-related changes in the budburst timing of its host tree (van Asch et al., 2012). In contrast, many species appear to be maladapted to changing climates, in part because factors such as limited existing genetic variation, weak heritability of adaptive traits, or conflicting constraints on adaptation create low potential for rapid evolution (Knudsen et al., 2011; Ketola et al., 2012; Merilä, 2012; Mihoub et al., 2012). Most studies of rapid evolution suffer from methodological

weaknesses, making it difficult to demonstrate clearly a genetic basis underlying observed phenotypic responses to environmental change (Gienapp et al., 2008; Franks and Hoffmann, 2012; Hansen et al., 2012; Merilä, 2012). Rapid advances in quantitative genetics, genomics, and phylogenetics, combined with recent progress on conceptual frameworks, will substantially improve the detection and attribution of genetic responses to changing climate over the next few years (Davis, C.C. et al., 2010; Salamin et al., 2010; Hoffmann and Sgro, 2011). In sum, there are few observational studies of rapid evolution and difficulties in detection and attribution, so there is only *medium confidence* that some species have responded to recent changes in climate through genetic adaptations, and insufficient evidence to determine if this is a widespread phenomenon (thus *low confidence* for detection and attribution across all species; Figure 4-4).

The ability of species to adapt to new environmental conditions through rapid evolutionary processes can also be inferred from the degree to which environmental niches are conserved when environment is changed. There is evidence that environmental niches are conserved for some species under some conditions (plants: Petitpierre et al., 2012; birds: Monahan and Tingley, 2012; review: Peterson et al., 2011), but also evidence suggesting that environmental niches can evolve over time scales of several decades following changes in climate (Broennimann et al., 2007; Angetter et al., 2011; Konarzewski et al., 2012; Leal and Gunderson, 2012; Lavergne et al., 2013). The paleontological record provides insight into evolutionary responses in the face of natural climate variation. In general, environmental niches appear to be broadly conserved through time although there are insufficient data to determine the extent to which genetic adaptation has attenuated range shifts and changes in population size (Peterson et al., 2011; Willis and MacDonald, 2011). Phylogeographic reconstructions of past species distributions suggest that hybridization may have helped avoid extinctions during cycles of glaciation and could also play a key role in future adaptation (Hegarty, 2012; Soliani et al., 2012). There is new evidence that epigenetic mechanisms, such as DNA methylation, could allow very rapid adaptation to climate (Paun et al., 2010; Zhang et al., 2013).

4.4.1.2.2. Mechanisms mediating rapid evolutionary response to future climate change

Studies of genetic variability across species ranges, and models that couple gene flow with spatially explicit population dynamics, suggest counterintuitive responses to climate change. Too much or too little gene flow to populations at range margins can create fragile, maladapted populations, which is in contrast to the current wisdom that populations at the range margins may be best adapted to global warming (Bridle et al., 2010; Hill et al., 2011). Conversely, there is evidence from experiments, models, and observations that populations in the center of species ranges may in some cases be more sensitive to environmental change than those at range boundaries (Bell and Gonzalez, 2009). Generalization is complicated by the interactions between local adaptation, gene flow, population dynamics, and species interactions (Bridle et al., 2010; Norberg et al., 2012).

Substantial progress has been made since AR4 in developing models for exploring whether genetic adaptation is fast enough to track climate change. Models of long-lived tree species suggest that existing genetic variation may be sufficient to slightly attenuate negative impacts of future climate change (Kuparinen et al., 2010; Kremer et al., 2012). However, these studies also indicate that adaptive responses will lag far behind even modest rates of projected climate change, owing to the very long generation time of trees. In a species with much shorter generation times, the great tit (*Parus major*), Gienapp et al. (2013) found that modeled avian breeding times tracked climate change, only at low to moderate rates of change. For a herbivorous insect with an even faster life cycle, van Asch et al. (2007, 2012) predicted that rapid evolution of the phenological response should have allowed it to track recent warming, which it has.

More broadly, models suggest that species with short generation times (1 year or less) potentially have the capacity to genetically adapt to even the most rapid rates of projected climate change given large enough present-day populations, but species with longer generation times or small populations could be at risk of extinction at moderate to high rates of climate change (Walters et al., 2012; Vedder et al., 2013). Recent experimental and theoretical work on "evolutionary rescue" shows that long-term avoidance of extinction through genetic adaptation to hostile environments is possible, but requires large initial genetic variation and population sizes and is accompanied by substantial loss of genetic diversity, reductions in population size, and range contractions over many generations before population recovery (Bell, 2013; Schiffers et al., 2013).

Model-based projections must be viewed with considerable caution because there are many evolutionary and ecological mechanisms not accounted for in most models that can either speed up or inhibit heritable adaptation to climate change (Cobben et al., 2012; Norberg et al., 2012; Kovach-Orr and Fussmann, 2013). In some cases, accounting for evolutionary processes in models even leads to predictions of greater maladaptation to climate change, resulting in rapid population declines (Hendry and Gonzalez, 2008; Ferriere and Legendre, 2013). Phenotypic plasticity is thought to generally improve the odds of adaptation to climate change. High plasticity in the face of climate change that has low fitness costs can greatly improve the odds of adaptation; however, plasticity with high costs leads to only modest amounts of adaptation (Chevin et al., 2010).

AR4 concluded that "projected rates of climate change are *very likely* to exceed rates of evolutionary adaptation in many species (*high confidence*)" (Fischlin et al., 2007). Work since then provides a similar, but more nuanced view of rapid evolution in the face of future climate change. The lack of adaptation in some species to recent changes in climate, broad support for niche conservatism, and models showing limited adaptive capacity in species with long generation times all indicate that high rates of climate change (RCP8.5) will exceed the adaptive capacities of many species (*high confidence*). On the other hand, evidence from observations and models also indicates that there is substantial capacity for genetic adaptation to attenuate phenological shifts, population declines, and local extinctions in many species, especially for low rates of climate change (RCP2.6) (*high confidence*). Projected adaptation to climate change is frequently characterized by population declines and loss of genetic diversity for many generations (*medium confidence*), thereby increasing species vulnerability to other pressures.

4.4.1.3. Migration of Species

This mode of adaptation has been extensively dealt with in Section 4.3.2.5. It is anticipated that the observed movement of species—individually and collectively—will continue in response to shifting climate patterns. Its effectiveness as an adaptation mechanism is constrained by three factors. First, the rate of migration for many species, in many regions of the world, is slower than the rate of movement of the climate envelope (see Figure 4-5). Second, the ecosystem interactions can remain intact only if all parts of the ecosystem migrate simultaneously and at the same rate. Third, the contemporary landscape and inland water systems contain many barriers to migration, in the form of habitat fragmentation, roads, human settlements, and dams. Mountain ecosystems are less constrained by these factors than flat-land ecosystems, but have additional impediments for species already close to the top of the mountain.

4.4.2. Human-Assisted Adaptation

Human-assisted adaptation means a deliberate intervention with the intent of increasing the capacity of the target organism, ecosystem, or socio-ecological system to survive and function at an acceptable level in the presence of climate change. It is also known as "planned adaptation" (Smit et al., 2007). This chapter focuses less on the adaptation of people, human communities, and infrastructure, as they are the topics of Chapters 8 to 17, and more on non-human organisms and ecosystems, while acknowledging the importance of the human elements within the ecosystem. Intervention in this context means a range of actions, including ensuring the presence of suitable habitat and dispersal pathways; reducing non-climate stressors; and physically moving organisms and storing and establishing them in new places. In addition to the other approaches assessed in this section, "Ecosystem-Based Adaptation" (see Box CC-EA) provides an option that integrates the use of biodiversity and ecosystem services into climate change adaptation strategies in ways that can optimize co-benefits for local communities and carbon management, as well as reduce the risks associated with possible maladaptation. Note that there are risks associated with all forms of human-assisted adaptation (see Section 4.4.4), particularly in the presence of far-from-perfect predictive capabilities (Willis and Bhagwat, 2009).

4.4.2.1. Reduction of Non-Climate Stresses and Restoration of Degraded Ecosystems

The alleviation of other stresses acting on ecosystems is suggested to increase the capacity of ecosystems to survive, and adapt to, climate change, as the effects are generally either additive or compounding. Ecosystem restoration is one way of alleviating such stresses while increasing the area available for adaptation (Harris et al., 2006). Building the resilience of at-risk ecosystems by identifying the full set of drivers of change and most important areas and resources for protection is the core of the adaptation strategy for the Arctic (Christie and Sommerkorn, 2012). Protective and restorative actions aimed at increasing resilience can also be a cost-effective means as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change and may have other social, economic, and cultural benefits. This is part of "ecosystem-based adaptation" (Colls et al., 2009; Box CC-EA).

4.4.2.2. The Size, Location, and Layout of Protected Areas

Additions to, or reconfigurations of, the protected area estate are commonly suggested as pre-adaptations to projected climate changes (Heller and Zavaleta, 2009). This is because for most protected areas, under plausible scenarios of climate change, a significant fraction of the biota will no longer have a viable population within the present protected area footprint. It is noted that the extant geography of protected areas is far from optimal for biodiversity protection even under the current climate; that most biodiversity exists outside rather than in protected areas and this between-protected area matrix is as important; that it is usually cheaper to acquire land proactively in the areas of projected future bioclimatic suitability than to correct the current non-optimality and then later add on areas to deal with climate change as it unfolds (Hannah et al., 2007); and that the existing protected area network will still have utility in future climates, even though it may contain different species (Thomas et al., 2012).

Hickler et al. (2012) analyzed the layout of protected areas in Europe and concluded that under projected 21st century climate change a third to a half of them would potentially be occupied by different vegetation than they currently represent. The new areas that need to be added to the existing protected area network to ensure future representativeness is situation specific, but some general design rules apply: orientation along climate gradients (e.g., altitudinal gradients) is more effective than orientation across them (Roux et al., 2008); regional scale planning is more effective than treating each local case independently because it is the network of habitats and protected areas that confers resilience rather than any single element (Heller and Zavaleta, 2009); and better integration of protected areas with a biodiversity-hospitable landscape outside is more effective than treating the protected areas as islands (Willis and Bhagwat, 2009). Dunlop et al. (2012) assessed the implications of climate change for biodiversity conservation in Australia and found many opportunities to facilitate the natural adaptation of biodiversity, including expanding the network of protected areas and restoring habitat at a large scale.

4.4.2.3. Landscape and Watershed Management

The need to include climate change into the management of vulnerable ecosystems is explicitly included in the strategic goals of the Convention on Biological Diversity. Oliver et al. (2012b) developed decision trees based on three scenarios: (1) *adversely sensitive*, where areas within the species current geographical range will become climatically unsuitable with a changing climate; (2) *climate overlap*, where there are areas that should remain climatically suitable within the species' range; and (3) *new climatic space*, which refers to areas outside of the current range that are projected to become suitable. Heller and Zavaleta (2009) reviewed recommendations in the published literature and argue that the majority of them, such as increase habitat heterogeneity of sites and connectivity of habitats across landscapes, lack sufficient specificity to ensure the persistence of many species and related ecosystem services to ongoing climate change. To date, recommendations are overwhelmingly focused on ecological data, neglecting social science insights. Few resources or capacity exist to guide adaptation planning processes at any scale.

Frequently Asked Questions

FAQ 4.6 | Can ecosystems be managed to help them and people to adapt to climate change?

The ability of human societies to adapt to climate change will depend, in large measure, on the management of terrestrial and inland freshwater ecosystems. A fifth of global human-caused carbon emissions today are absorbed by terrestrial ecosystems; this important carbon sink operates largely without human intervention, but could be increased through a concerted effort to reduce forest loss and to restore damaged ecosystems, which also co-benefits the conservation of biodiversity.

The clearing and degradation of forests and peatlands represents a source of carbon emissions to the atmosphere which can be reduced through management; for instance, there has been a three-quarters decline in the rate of deforestation in the Brazilian Amazon in the last 2 decades. Adaptation is also helped through more proactive detection and management of wildfire and pest outbreaks, reduced drainage of peatlands, the creation of species migration corridors, and assisted migration.

Climate-induced impacts to hydrological and thermal regimes in freshwater systems can be offset through improved management of environmental flow releases from reservoirs (Arthington et al., 2006, 2010 and references therein; Poff et al., 2010). Protection and restoration of riparian vegetation in small stream systems provide an effective strategy to moderate temperature regimes and offset warming, and protect water quality for downstream ecosystems and water supply areas (Davies, 2010; Capon et al., 2013).

General principles for management adaptations were summarized from a major literature review by West et al. (2009). They suggest that in the context of climate change, successful management of natural resources will require cycling between "managing for resilience" and "managing for change." This requires the anticipation of changes that can alter the impacts of grazing, fire, logging, harvesting, recreation, and so on. At the national level, principles to facilitate adaptation include (1) management at appropriate scales, and not necessarily the scales of convenience or tradition; (2) increased collaboration among agencies; (3) rational approaches for establishing priorities and applying triage; and (4) management with the expectation of ecosystem change, rather than keeping them as they have been. Barriers and opportunities were divided into four categories: (1) legislation and regulations, (2) management policies and procedures, (3) human and financial capital, and (4) information and science.

Steenberg et al. (2011) simulated the effect on adaptive capacity of three variables related to timber harvesting: the canopy-opening size of harvests, the age of harvested trees within a stand, and the species composition of harvested trees within a stand. The combination of all three adaptation treatments allowed target species and old forest to remain reasonably well represented without diminishing the timber supply. This minimized the trade-offs between management values and climate adaptation objectives. Manipulation of vegetation composition and stand structure has been proposed as a strategy for offsetting climatic change impacts on wildfires in Canada. Large areas of boreal forests are currently being harvested and there may be opportunities for using planned manipulation of vegetation for management of future wildfire risks. This management option could also provide an additional benefit to the use of assisted species migration because the latter would require introducing non-flammable broadleaves species into forests that are otherwise highly flammable (Girardin et al., 2013b; Terrier et al., 2013). Harvesting practices, such as partial cuts that limit the opening of the forest cover created by harvest, will be a key element to maintain diverse forest compositions and age class distributions in boreal forests. Another sound option for decreasing the exposure of silvicultural investments to an increasing fire danger is to use tree species requiring a shorter rotation (Girardin et al., 2013a).

4.4.2.4. Assisted Migration

Assisted migration has been proposed when fragmentation of habitats limits migration potential or when natural migration rates are outstripped by the pace of climate change (Hoegh-Guldberg et al., 2008; Vitt et al., 2010; Chmura et al., 2011; Loss et al., 2011; Ste-Marie et al., 2011). The options for management can be summarized as: (1) try to maintain or improve existing habitat or environment so that species do not have to move (e.g., Settele and Kühn, 2009); (2) maintain or improve migration corridors, including active management to improve survival along the moving margin of the distribution (Lawson et al., 2012); and (3) directly translocate species or genetically distinct populations within a species (Aitken et al., 2008; Hoegh-Guldberg et al., 2008; Rehfeldt and Jaquish, 2010; Loss et al., 2011; Pedlar et al., 2012). There is *low agreement* whether it is better to increase the resilience to climate change of ecosystems as they currently occur, or to enhance capacity of ecosystems to transform in the face of climate change (Richardson et al., 2009).

There is *high agreement* that maintaining or improving migration corridors or ecological networks is a low-regret strategy, partly because it is also seen as useful in combatting the negative effects of habitat fragmentation on population dynamics (Hole et al., 2011; Jongman et al., 2011). This approach has the benefit of improving the migration potential for large numbers of species and is therefore a more ecosystem-wide approach than assisted migration for individual species. However, observational and modeling studies show that increases in habitat connectivity do not always improve the population dynamics of target

species, may decrease species diversity, and may also facilitate the spread of invasive species (Cadotte, 2006; Brisson et al., 2010; Matthiessen et al., 2010).

There is *medium agreement* that the practice of assisted migration of targeted species is a useful adaptation option (Hoegh-Guldberg et al., 2008; Vitt et al., 2009; Willis and Bhagwat, 2009; Loss et al., 2011; Hewitt et al., 2011). The velocity of 21st century climate change and substantial habitat fragmentation in large parts of the world means that many species will be unable to migrate or adapt fast enough to keep pace with climate change (Figure 4-5), posing problems for long-term survival of the species. Some ecologists believe that careful selection of species to be moved would minimize the risk of undesirable impacts on existing communities or ecosystem function (Minteer and Collins, 2010), but others argue that the history of intentional species introductions shows that the outcomes are unpredictable and in many cases have had disastrous impacts (Ricciardi and Simberloff, 2009). The number of species that require assisted migration could easily overwhelm funding capacity (Minteer and Collins, 2010). Decisions regarding which species should be translocated are complex and debatable, given variability among and within species and the ethical issues involved (Aubin et al., 2011; Winder, R. et al., 2011).

4.4.2.5. *Ex Situ* Conservation

Conservation of plant and animal genetic resources outside of their natural environment—in gardens, zoos, breeding programs, seed banks, or gene banks—has been widely advocated as an "insurance" against both climate change and other sources of biodiversity loss and impoverishment (Khoury et al., 2010). There are many examples of existing efforts of this type, some with global scope (e.g., Millennium Seed Bank, Svalbard Vault, Frozen Ark, Global Genome Initiative, and others; Lermen et al., 2009; Rawson et al., 2011). Knowledge of which genetic variants within a species have more potential for adaptation to climate change could help prioritize the material stored (Michalski et al., 2010).

Several issues remain largely unresolved (Li and Pritchard, 2009). The physiological, institutional, and economic sustainability of such efforts into the indefinite future is unclear. The fraction of the intraspecific variation that needs to be preserved for future viability and how much genetic bias is introduced by collecting relatively small samples from restricted locations, and then later by the selection pressures inadvertently applied during *ex situ* maintenance are unknown. Despite some documented successes, it remains uncertain whether it is always possible to reintroduce species successfully into the wild after generations of *ex situ* conservation.

4.4.3. Consequences and Costs of Inaction and Benefits of Action

Failure to reduce the magnitude or rate of climate change will plausibly lead to changes (often decreases) in the value of ecosystem services provided, or incur costs in order to maintain or restore the services or adapt to their decline. There are several sources of such costs: administration and assessment, implementation, and opportunity costs, including financial cost. Owing to the number of assumptions made, knowledge gaps, and recognized uncertainties, such result should be employed with caution. A systematic review of costs related to ecosystems and climate change by Rodriguez-Labajos (2013) shows that the monetary and non-monetary costs are distributed across all ecosystem service categories. It also discusses the potential and limits of monetary cost calculations, and issues of timing, trade-offs, and the unequal distribution of costs.

A comprehensive monetary estimate of the effects of climate change on ecosystem service provision is not available. The Millennium Ecosystem Assessment (2005c,d,e) included climate change among the direct drivers of ecosystems change and devoted a chapter to the necessary responses. Building on results of the IPCC, the Millennium Ecosystem Assessment offered some estimated costs of action: complying with the Kyoto protocol for industrial countries would range between 0.2 and 2% of GDP; a modest stabilization target of 450 ppm CO_2 in the atmosphere over the 21st century would range from 0.02 to 0.1% of global-average GDP per year. TEEB (2009) underlined priorities in the ecosystem service-climate change coupling (reduction targets in relation to coral reefs, forest carbon markets and accounting, and ecosystem investment for mitigation), without going in depth into analysis of the cost types involved. The Cost of Policy Inaction (COPI) Project (ten Brink et al., 2008) estimated the monetary costs of not meeting the 2010 biodiversity goals. Their model incorporates climate change, among other pressures, through an impaired quality of land, in terms of species abundance in diverse land use categories. They conclude that the cumulative losses

Frequently Asked Questions

FAQ 4.7 | What are the economic costs of changes in ecosystems due to climate change?

Climate change will certainly alter the services provided by most ecosystems, and for high degrees of change, the overall impacts are most likely to be negative. In standard economics, the value of services provided by ecosystems are known as externalities, which are usually outside the market price system, difficult to evaluate, and often ignored.

A good example is the pollination of plants by bees and birds and other species, a service that may be negatively affected by climate change. Pollination is critical for the food supply as well as for overall environmental health. Its value has been estimated globally at US$350 billion for the year 2010 (range of estimates of US$200 to 500 billion).

of welfare due to land use changes, in terms of loss of ecosystem services, could reach an annual amount of EUR 14 trillion (based on 2007 values) in 2050, which may be equivalent to 7% of projected global GDP for that year. Eliasch (2008) estimates the damage costs to forests as reaching US$1 trillion a year by 2100. The study used the probabilistic model employed by Stern (2006), which did not value effects on biodiversity or water-related ecosystem services.

The studies to date agree on the following points. First, climate change has already caused a reduction in ecosystem services that will become more severe as climate change continues. Second, ecosystem-based strategies to mitigate climate change are cost effective, although more difficult to implement (i.e., more costly) in intensively managed ecosystems such as farming lands. Third, accurately estimating the monetary costs of reduction in ecosystem services that are not marketed is difficult. The provision of monetized costs tends to sideline the non-monetized political, social, and environmental costs relevant for decision making. Finally, there is a large funding gap between the cost of actions necessary to protect ecosystem services against climate change and the actual resources available.

In addition to direct costs, further costs may result from trade-offs between services: for example, afforestation for climate mitigation and urban greening for climate adaptation may be costly in terms of water provision (Chisholm, 2010; Jenerette et al., 2011; Pataki et al., 2011). Traditional agriculture preserves soil carbon sinks, supports on-site biodiversity, and uses less fossil fuel than high-input agriculture (Martinez-Alier, 2011) but, due to the typically lower per hectare yields, may require a larger area to be dedicated to cropland. Leaving aside the contested (Searchinger et al., 2008; Plevin et al., 2010) effectiveness of biofuels as a mitigation strategy, there is evidence of their disruptive effect on food security, land tenure, labor rights, and biodiversity in several parts of the world (Obersteiner et al., 2010; Tirado et al., 2010).

4.4.4. Unintended Consequences of Adaptation and Mitigation

Actions taken within the terrestrial and freshwater system domain or in other sectors to mitigate or adapt to climate change can have unintended consequences. Some issues relevant to this section are also found in Section 14.7 and the Working Group III contribution to the AR5.

Several of the alternatives to fossil fuel require extensive use of the land surface and thus have a direct impact on terrestrial ecosystems and an indirect impact on inland water systems (Paterson et al., 2008; Turner et al., 2010). As an illustration, the RPC2.6 scenario involves both bioenergy and renewables as major components of the energy mix (Box 4-1; van Vuuren et al., 2011).

Policy shifts in developed countries favor the expansion of large-scale bioenergy production, which places new pressures on terrestrial and freshwater ecosystems (Searchinger et al., 2008; Lapola et al., 2010), either through direct use of land or water or indirectly by displacing food crops, which must then be grown elsewhere. Over the past decade there has been a global trend to reduced rates of forest loss; it is unclear if this will continue in the face of simultaneously rising food and biofuel demand (Wise et al., 2009; Meyfroidt and Lambin, 2011). The EU Renewable Energy Sources Directive is estimated to have only a moderate influence on European forests provided that the price paid by the bioenergy producers remained below US$50 to 60 per cubic meter of wood (Moiseyev et al., 2011). However, a doubled growth rate for bioenergy until 2030 would have major consequences for the global forest sector, including a reduction of forest stocks in Asia of 2 to 4% (Buongiorno et al. 2011). By 2100 in RCP2.6, bioenergy crops are projected to occupy approximately 4 million km^2, about 7% of global cultivated land projected at the time. Modification of the landscape and the fragmentation of habitats are major influences on extinction risks (Fischer and Lindenmayer, 2007), especially if native vegetation cover is reduced or degraded, human land use is intensive, and "natural" areas become disconnected. Hence, additional extensification of cultivated areas for energy crops may contribute to extinction risks. Some bioenergy crops may be invasive species (Raghu et al., 2006).

Abandoned former agricultural land could be used for biomass production (McAlpine et al., 2009). However, such habitats may be core elements in cultural landscapes of high conservation value, with European species-rich grasslands often developed from abandoned croplands (Hejcman et al., 2013).

Damming of river systems for hydropower can cause fragmentation of the inland water habitat with implications for fish species, and monitoring studies indicate that flooding of ecosystems behind the dams can lead to declining populations, for example, of amphibians (Brandão and Araújo, 2007). Reservoirs can be a sink of CO_2 but also a source of biogenic CO_2 and CH_4; this issue is discussed in WG III AR5 Section 7.8.1.

Wind turbines can kill birds and bats (e.g., Barclay et al., 2007), and inappropriately sited wind farms can negatively impact on bird populations (Drewitt and Langston, 2006). Effects can be reduced by careful siting of turbines, for example by avoiding migration routes (Drewitt and Langston, 2006). Estimating mortality rates is complex and difficult (Smallwood, 2007) but techniques are being developed to inform siting decisions and impact assessments (Péron et al., 2013). Wind farms in Europe and the USA are estimated to cause between 0.3 and 0.4 wildlife fatalities per gigawatt-hour of electricity, compared to approximately 5.2 wildlife fatalities per gigawatt-hour for nuclear and fossil-fuel power stations (Sovacool, 2009; but see Willis, C.K.R. et al., 2010). One study found on-site bird populations to be generally affected more by windfarm construction than subsequent operation, with some populations recovering after construction (Pearce-Higgins et al., 2012).

Large-scale solar farms could impact local biodiversity if poorly sited, but the impact can be reduced with appropriate planning (Tsoutsos et al., 2005). Solar photovoltaic installations can decrease local surface albedo, giving a small positive radiative forcing. There are some plausible local circumstances in which this may be a consideration, but in general the climate effect is estimated to be 30 times smaller than the avoided radiative forcing arising from substituting fossil fuels with PV (Nemet, 2009).

Relocation or expansion of agricultural areas and settlements as climate change adaptation measures could pose risks of habitat fragmentation and loss similar to those discussed above in the context of mitigation

through bio-energy. Assisted migration (see Section 4.4.2.4) may directly conflict with other conservation priorities, for example by facilitating the introduction of invasive species (Maclachlan et al., 2007).

4.5. Emerging Issues and Key Uncertainties

Detecting the presence and location of thresholds in ecosystem response to climate change, specifically the type of thresholds characterized as tipping points, remains a major source of uncertainty with high potential consequences. In general (Field et al., 2007), negative feedbacks currently dominate the climate-ecosystem interaction. For most ecological processes, increasing magnitude of warming shifts the balance toward positive rather than negative feedbacks (Field et al., 2007). In several regions, such as the boreal ecosystems, positive feedbacks may become dominant, under moderate warming. For positive feedbacks to propagate into "runaway" processes leading to a new ecosystem state, the strength of the feedback has to exceed that of the initial perturbation. This has not as yet been demonstrated for any large-scale, plausible, and immanent ecological process, but the risk is non-negligible and the consequences if it did occur would be severe; thus further research is needed.

The issue of biophysical interactions between ecosystem state and the climate, over and above the effects mediated through GHGs, is emerging as significant in many areas. Such effects include those caused by changes in surface reflectivity (albedo) or the partitioning of energy between latent energy and sensible heat.

Uncertainty in predicting the response of terrestrial and freshwater ecosystems to climate and other perturbations, particularly at the local scale, remains a major impediment to determining prudent levels of permissible change. A significant source of this uncertainty stems from the inherent complexity of ecosystems, especially where they are coupled to equally complex social systems. The high number of interactions can lead to cascading effects (Biggs et al., 2011). Some of this uncertainty can be reduced by better systems understanding, but some will remain irreducible because of the failure of predictive models when faced with certain types of complexity (such as those which lead to mathematical bifurcations, a problem that is well known in climate science). Probabilistic statements about the range of outcomes are possible in this context, but ecosystem science is as yet mostly unable to conduct such analyses routinely and rigorously. One consequence is the ongoing difficulty in attributing observed changes unequivocally to climate change. More comprehensive monitoring is a key element of the solution.

The consequences for species interactions of differing phenological or movement-based responses to climate change are insufficiently known and may make projections based on individual species models unreliable.

Studies of the combined effects of multiple simultaneous elements of global change, such as the effects of elevated CO_2 and rising tropospheric ozone on plant productivity—which have critical consequences for the future sink strength of the biosphere, as they are of similar magnitude but opposite sign—are needed as a supplement to the single-factor experiments. For example, uncertainty on the magnitude of CO_2 fertilization is key for forest responses to climate change, particularly in tropical forests, woodlands, and savannas (Cox et al., 2013; Huntingford et al., 2013).

The effects of changes in the frequency or intensity of climate-related extreme events, such as floods, cyclones, heat waves, and exceptionally large fires on ecosystem change are probably equal to or greater than shifts in the mean values of climate variables. These effects are insufficiently studied and, in particular, are seldom adequately represented in ESMs.

Understanding of the rate of climate change that can be tracked or adapted to by organisms is as important as understanding the magnitude of change they can tolerate. Despite being explicitly required under Article 2 of the UNFCCC, rate studies are currently less developed and more uncertain than magnitude (equilibrium) studies. This includes evidence for the achievable migration rates of a range of species as well as the rate of micro-evolutionary change.

The capacity for, and limits to, ecological and evolutionary adaptive processes are known only in a few cases. The development and testing of human-assisted adaptation strategies for their cost-effectiveness in reducing risk are prerequisites for their widespread adoption.

The costs of the loss of biodiversity and ecosystem services as a result of climate change are known for only a few cases, or are associated with large uncertainties, as are the costs and benefits of assisting ecosystems and species to adapt to climate change.

References

Aakala, T., T. Kuuluvainen, T. Wallenius, and H. Kauhanen, 2011: Tree mortality episodes in the intact Picea abies-dominated taiga in the Arkhangelsk region of northern European Russia. *Journal of Vegetation Science*, **22(2)**, 322-333.

Abatzoglou, J.T. and C.A. Kolden, 2011: Climate change in western US deserts: potential for increased wildfire and invasive annual grasses. *Rangeland Ecology & Management*, **64(5)**, 471-478.

Adamik, P. and M. Kral, 2008: Climate- and resource-driven long-term changes in dormice populations negatively affect hole-nesting songbirds. *Journal of Zoology*, **275(3)**, 209-215.

Adamik, P. and J. Pietruszkova, 2008: Advances in spring but variable autumnal trends in timing of inland wader migration. *Acta Ornithologica*, **43(2)**, 119-128.

Adams, H.D., C.H. Luce, D.D. Breshears, C.D. Allen, M. Weiler, V.C. Hale, A.M.S. Smith, and T.E. Huxman, 2012: Ecohydrological consequences of drought- and infestation-triggered tree die-off: insights and hypotheses. *Ecohydrology*, **5(2)**, 145-159.

Adrian, R., C.M. O'Reilly, H. Zagarese, S.B. Baines, D.O. Hessen, W. Keller, D.M. Livingstone, R. Sommaruga, D. Straile, E. Van Donk, G.A. Weyhenmeyer, and M. Winder, 2009: Lakes as sentinels of climate change. *Limnology and Oceanography*, **54(6)**, 2283-2297.

Ahl, D.E., S.T. Gower, S.N. Burrows, N.V. Shabanov, R.B. Myneni, and Y. Knyazikhin, 2006: Monitoring spring canopy phenology of a deciduous broadleaf forest using MODIS. *Remote Sensing of Environment*, **104(1)**, 88-95.

Ahola, M.P., T. Laaksonen, T. Eeva, and E. Lehikoinen, 2007: Climate change can alter competitive relationships between resident and migratory birds. *Journal of Animal Ecology*, **76(6)**, 1045-1052.

Aiello-Lammens, M.E., M.L. Chu-Agor, M. Convertino, R.A. Fischer, I. Linkov, and H.R. Akcakaya, 2011: The impact of sea-level rise on Snowy Plovers in Florida: integrating geomorphological, habitat, and metapopulation models. *Global Change Biology*, **17(12)**, 3644-3654.

Ainsworth, E.A., C.R. Yendrek, S. Sitch, W.J. Collins, and L.D. Emberson, 2012: The effects of tropospheric ozone on net primary productivity and implications for climate change. *Annual Review of Plant Biology*, **63(1)**, 637-661.

Aitken, S.N., S. Yeaman, J.A. Holliday, T.L. Wang, and S. Curtis-McLane, 2008: Adaptation, migration or extirpation: climate change outcomes for tree populations. *Evolutionary Applications*, **1(1)**, 95-111.

Alahuhta, J., J. Heino, and M. Luoto, 2011: Climate change and the future distributions of aquatic macrophytes across boreal catchments. *Journal of Biogeography*, **38(2)**, 383-393.

Albert, K.R., J. Kongstad, I.K. Schmidt, H. Ro-Poulsen, T.N. Mikkelsen, A. Michelsen, L. van der Linden, and C. Beier, 2012: Temperate heath plant response to dry conditions depends on growth strategy and less on physiology. *Acta Oecologica-International Journal of Ecology*, **45**, 79-87.

Albert, K.R., H. Ro-Poulsen, T.N. Mikkelsen, A. Michelsen, L. Van der Linden, and C. Beier, 2011: Effects of elevated CO_2, warming and drought episodes on plant carbon uptake in a temperate heath ecosystem are controlled by soil water status. *Plant Cell and Environment*, **34(7)**, 1207-1222.

Aldous, A., J. Fitzsimons, B. Richter, and L. Bach, 2011: Droughts, floods and freshwater ecosystems: evaluating climate change impacts and developing adaptation strategies. *Marine and Freshwater Research*, **62(3)**, 223-231.

Alencar, A., D.C. Nepstad, and M.d.C. Vera Diaz, 2006: Forest understory fire in the Brazilian Amazon in ENSO and non-ENSO years: area burned and committed carbon emissions. *Earth Interactions*, **10**, 6, 1-17, doi:10.1175/EI150.1.

Alencar, A., G.P. Asner, D. Knapp, and D. Zarin, 2011: Temporal variability of forest fires in eastern Amazonia. *Ecological Applications*, **21(7)**, 2397-2412.

Alexander, H.D., M.C. Mack, S. Goetz, M. Loranty, P.S.A. Beck, K. Earl, S. Zimov, S. Davydov, and C.C. Thompson, 2012: Carbon accumulation patterns during post-fire succession in cajander larch (*Larix cajanderi*) forests of Siberia. *Ecosystems*, **15**, 1065-1082.

Ali, A.A., O. Blarquez, M.P. Girardin, C. Hely, F. Tinquaut, A. El Guellab, V. Valsecchi, A. Terrier, L. Bremond, A. Genries, S. Gauthier, and Y. Bergeron, 2012: Control of the multimillennial wildfire size in boreal North America by spring climatic conditions. *Proceedings of the National Academy of Sciences of the United States of America*, **109(51)**, 20966-20970.

Alkama, R., M. Kageyama, and G. Ramstein, 2012: A sensitivity study to global desertification in cold and warm climates: results from the IPSL OAGCM model. *Climate Dynamics*, **38(7-8)**, 1629-1647.

Alkemade, R., M. van Oorschot, L. Miles, C. Nellemann, M. Bakkenes, and B. ten Brink, 2009: GLOBIO3: a framework to investigate options for reducing global terrestrial biodiversity loss. *Ecosystems*, **12(3)**, 374-390.

Allan, J.D., 2004: Landscapes and riverscapes: The influence of land use on stream ecosystems. *Annual Review of Ecology Evolution and Systematics*, **35**, 257-284.

Allen, C.D., A.K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D.D. Breshears, E.H. Hogg, P. Gonzalez, R. Fensham, Z. Zhang, J. Castro, N. Demidova, J.H. Lim, G. Allard, S.W. Running, A. Semerci, and N. Cobb, 2010: A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, **259(4)**, 660-684.

Allen, J.R.M., T. Hickler, J.S. Singarayer, M.T. Sykes, P.J. Valdes, and B. Huntley, 2010: Last glacial vegetation of northern Eurasia. *Quaternary Science Reviews*, **29(19-20)**, 2604-2618.

Alley, R.B., J. Marotzke, W.D. Nordhaus, J.T. Overpeck, D.M. Peteet, R.A. Pielke, R.T. Pierrehumbert, P.B. Rhines, T.F. Stocker, L.D. Talley, and J.M. Wallace, 2003: Abrupt climate change. *Science*, **299(5615)**, 2005-2010.

Anchukaitis, K.J. and M.N. Evans, 2010: Tropical cloud forest climate variability and the demise of the Monteverde golden toad. *Proceedings of the National Academy of Sciences of the United States of America*, **107(11)**, 5036-5040.

Anderegg, W.R.L., L.D.L. Anderegg, C. Sherman, and D.S. Karp, 2012: Effects of widespread drought-induced aspen mortality on understory plants. *Conservation Biology*, **26(6)**, 1082-1090.

Anderegg, W.R.L., J.M. Kane, and L.D.L. Anderegg, 2013a: Consequences of widespread tree mortality triggered by drought and temperature stress. *Nature Climate Change*, **3(1)**, 30-36.

Anderegg, W.R.L., L. Plavcová, L.D.L. Anderegg, U.G. Hacke, J.A. Berry, and C.B. Field, 2013b: Drought's legacy: multiyear hydraulic deterioration underlies widespread aspen forest die-off and portends increased future risk. *Global Change Biology*, **19(4)**, 1188-1196.

Anderson, J.T., A.M. Panetta, and T. Mitchell-Olds, 2012a: Evolutionary and ecological responses to anthropogenic climate change. *Plant Physiology*, **160(4)**, 1728-1740.

Anderson, J.T., D.W. Inouye, A.M. McKinney, R.I. Colautti, and T. Mitchell-Olds, 2012b: Phenotypic plasticity and adaptive evolution contribute to advancing flowering phenology in response to climate change. *Proceedings of the Royal Society B*, **279(1743)**, 3843-3852.

Anderson, R.G., J.G. Canadell, J.T. Randerson, R.B. Jackson, B.A. Hungate, D.D. Baldocchi, G.A. Ban-Weiss, G.B. Bonan, K. Caldeira, L. Cao, N.S. Diffenbaugh, K.R. Gurney, L.M. Kueppers, B.E. Law, S. Luyssaert, and T.L. O'Halloran, 2011: Biophysical considerations in forestry for climate protection. *Frontiers in Ecology and the Environment*, **9(3)**, 174-182.

Andreae, M.O., D. Rosenfeld, P. Artaxo, A.A. Costa, G.P. Frank, K.M. Longo, and M.A.F. Silva-Dias, 2004: Smoking rain clouds over the Amazon. *Science*, **303**, 1337-1342.

Andreu-Hayles, L., O. Planells, E. Gutiérrez, E. Muntan, G. Helle, K.J. Anchukaitis, and G.H. Schleser, 2011: Long tree-ring chronologies reveal 20th century increases in water-use efficiency but no enhancement of tree growth at five Iberian pine forests. *Global Change Biology*, **17(6)**, 2095-2112.

Angassa, A. and G. Oba, 2008: Effects of management and time on mechanisms of bush encroachment in southern Ethiopia. *African Journal of Ecology*, **46(2)**, 186-196.

Angeler, D.G. and W. Goedkoop, 2010: Biological responses to liming in boreal lakes: an assessment using plankton, macroinvertebrate and fish communities. *Journal of Applied Ecology*, **47(2)**, 478-486.

Angert, A.L., L.G. Crozier, L.J. Rissler, S.E. Gilman, J.J. Tewksbury, and A.J. Chunco, 2011: Do species' traits predict recent shifts at expanding range edges? *Ecology Letters*, **14(7)**, 677-689.

Angetter, L.S., S. Lotters, and D. Rodder, 2011: Climate niche shift in invasive species: the case of the brown anole. *Biological Journal of the Linnean Society*, **104(4)**, 943-954.

Anyamba, A. and C.J. Tucker, 2005: Analysis of Sahelian vegetation dynamics using NOAA-AVHRR NDVI data from 1981-2003. *Journal of Arid Environments*, **63(3)**, 596-614.

Aragão, L., Y. Malhi, N. Barbier, A. Lima, Y. Shimabukuro, L. Anderson, and S. Saatchi, 2008: Interactions between rainfall, deforestation and fires during recent years in the Brazilian Amazonia. *Philosophical Transactions of the Royal Society B*, **363(1498)**, 1779-1785.

Araujo, M.B. and A.T. Peterson, 2012: Uses and misuses of bioclimatic envelope modeling. *Ecology*, **93(7)**, 1527-1539.

Araujo, M.B., D. Alagador, M. Cabeza, D. Nogues-Bravo, and W. Thuiller, 2011: Climate change threatens European conservation areas. *Ecology Letters*, **14(5)**, 484-492.

Archibald, S., D.P. Roy, B.W. van Wilgen, and R.J. Scholes, 2009: What limits fire? An examination of drivers of burnt area in southern Africa. *Global Change Biology*, **15(3)**, 613-630.

Arenas, M., N. Ray, M. Currat, and L. Excoffier, 2012: Consequences of range contractions and range shifts on molecular diversity. *Molecular Biology and Evolution*, **29(1)**, 207-218.

Arismendi, I., S.L. Johnson, J.B. Dunham, R. Haggerty, and D. Hockman-Wert, 2012: The paradox of cooling streams in a warming world: Regional climate trends do not parallel variable local trends in stream temperature in the Pacific continental United States. *Geophysical Research Letters*, **39**, L10401, doi:10.1029/2012GL051448.

Armenteras-Pascual, D., J. Retana-Alumbreros, R. Molowny-Horas, R.M. Roman-Cuesta, F. Gonzalez-Alonso, and M. Morales-Rivas, 2011: Characterising fire spatial pattern interactions with climate and vegetation in Colombia. *Agricultural and Forest Meteorology*, **151(3)**, 279-289.

Arneth, A., S.P. Harrison, S. Zaehle, K. Tsigaridis, S. Menon, P.J. Bartlein, J. Feichter, A. Korhola, M. Kulmala, D. O'Donnell, G. Schurgers, S. Sorvari, and T. Vesala, 2010: Terrestrial biogeochemical feedbacks in the climate system. *Nature Geoscience*, **3(8)**, 525-532.

Arora, V.K. and A. Montenegro, 2011: Small temperature benefits provided by realistic afforestation efforts. *Nature Geoscience*, **4(8)**, 514-518.

Arthington, A.H., S.E. Bunn, N.L. Poff, and R.J. Naiman, 2006: The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications*, **16(4)**, 1311-1318.

Arthington, A.H., R.J. Naiman, M.E. McClain, and C. Nilsson, 2010: Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities. *Freshwater Biology*, **55(1)**, 1-16.

Ask, J., J. Karlsson, L. Persson, P. Ask, P. Bystrom, and M. Jansson, 2009: Terrestrial organic matter and light penetration: Effects on bacterial and primary production in lakes. *Limnology and Oceanography*, **54(6)**, 2034-2040.

Aubin, I., C.M. Garbe, S. Colombo, C.R. Drever, D.W. McKenney, C. Messier, J. Pedlar, M.A. Saner, L. Venier, A.M. Wellstead, R. Winder, E. Witten, and C. Ste-Marie, 2011: Why we disagree about assisted migration: ethical implications of a key

debate regarding the future of Canada's forests. *Forestry Chronicle*, **87(6)**, 755-765.

Aufdenkampe, A.K., E. Mayorga, P.A. Raymond, J.M. Melack, S.C. Doney, S.R. Alin, R.E. Aalto, and K. Yoo, 2011: Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. *Frontiers in Ecology and the Environment*, **9(1)**, 53-60.

Axford, Y., J.P. Briner, C.A. Cooke, D.R. Francis, N. Michelutti, G.H. Miller, J.P. Smol, E.K. Thomas, C.R. Wilson, and A.P. Wolfe, 2009: Recent changes in a remote Arctic lake are unique within the past 200,000 years. *Proceedings of the National Academy of Sciences of the United States of America*, **106(44)**, 18443-18446.

Baccini, A., S.J. Goetz, W.S. Walker, N.T. Laporte, M. Sun, D. Sulla-Menashe, J. Hackler, P.S.A. Beck, R. Dubayah, M.A. Fiedl, S. Samanta, and R.A. Houghton, 2012: Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nature Climate Change*, **2(3)**, 182-185.

Bai, Z.G., D.L. Dent, L. Olsson, and M.E. Schaepman, 2008: Proxy global assessment of land degradation. *Soil Use and Management*, **24(3)**, 223-234.

Bala, G., K. Caldeira, M. Wickett, T.J. Phillips, D.B. Lobell, C. Delire, and A. Mirin, 2007: Combined climate and carbon-cycle effects of large-scale deforestation. *Proceedings of the National Academy of Sciences of the United States of America*, **104(16)**, 6550-6555.

Balch, J.K., D.C. Nepstad, P.M. Brando, L.M. Curran, O. Portela, O. de Carvalho, and P. Lefebvre, 2008: Negative fire feedback in a transitional forest of southeastern Amazonia. *Global Change Biology*, **14(10)**, 2276-2287.

Balian, E.V., H. Segers, C. Leveque, and K. Martens, 2008: The freshwater animal diversity assessment: an overview of the results. *Hydrobiologia*, **595(1)**, 627-637.

Balint, M., S. Domisch, C.H.M. Engelhardt, P. Haase, S. Lehrian, J. Sauer, K. Theissinger, S.U. Pauls, and C. Nowak, 2011: Cryptic biodiversity loss linked to global climate change. *Nature Climate Change*, **1(6)**, 313-318.

Ball, J.T., I.E. Woodrow, and J.A. Berry, 1987: A model predicting stomatal conductance and its to the control of photosynthesis under different environmental conditions. In: *Progress in Photosynthesis Research: Proceedings of the VIIth International Congress on Photosynthesis, Providence, Rhode Island, USA, August 10-15, Vol. 2* [Biggins, I. (ed.)]. Martinus Nijhoff Publishers, Leiden, Netherlands, pp. 221-224.

Barber, V.A., G.P. Juday, and B.P. Finney, 2000: Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. *Nature*, **405(6787)**, 668-673.

Barbet-Massin, M., W. Thuiller, and F. Jiguet, 2012: The fate of European breeding birds under climate, land-use and dispersal scenarios. *Global Change Biology*, **18(3)**, 881-890.

Barbosa, I.C.R., I.H. Koehler, K. Auerswald, P. Lups, and S. Hans, 2010: Last-century changes of alpine grassland water-use efficiency: a reconstruction through carbon isotope analysis of a time-series of Capra ibex horns. *Global Change Biology*, **16(4)**, 1171-1180.

Barbraud, C. and H. Weimerskirch, 2006: Antarctic birds breed later in response to climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **103(16)**, 6248-6251.

Barbraud, C., M. Gavrilo, Y. Mizin, and H. Weimerskirch, 2011: Comparison of emperor penguin declines between Pointe Geologie and Haswell Island over the past 50 years. *Antarctic Science*, **23(5)**, 461-468.

Barclay, R.M.R., E.F. Baerwald, and J.C. Gruver, 2007: Variation in bat and bird fatalities at wind energy facilities: assessing the effects of rotor size and tower height. *Canadian Journal of Zoology / Revue Canadienne De Zoologie*, **85(3)**, 381-387.

Barlow, J. and C.A. Peres, 2008: Fire-mediated dieback and compositional cascade in an Amazonian forest. *Philosophical Transactions of the Royal Society B*, **363(1498)**, 1787-1794.

Barnosky, A.D., N. Matzke, S. Tomiya, G.O.U. Wogan, B. Swartz, T.B. Quental, C. Marshall, J.L. McGuire, E.L. Lindsey, K.C. Maguire, B. Mersey, and E.A. Ferrer, 2011: Has the Earth's sixth mass extinction already arrived? *Nature*, **471(7336)**, 51-57.

Barnosky, A.D., E.A. Hadly, J. Bascompte, E.L. Berlow, J.H. Brown, M. Fortelius, W.M. Getz, J. Harte, A. Hastings, P.A. Marquet, N.D. Martinez, A. Mooers, P. Roopnarine, G. Vermeij, J.W. Williams, R. Gillespie, J. Kitzes, C. Marshall, N. Matzke, D.P. Mindell, E. Revilla, and A.B. Smith, 2012: Approaching a state shift in Earth's biosphere. *Nature*, **486(7401)**, 52-58.

Bartholow, J.M., 2005: Recent water temperature trends in the lower Klamath River, California. *North American Journal of Fisheries Management*, **25(1)**, 152-162.

Bartomeus, I., J.S. Ascher, D. Wagner, B.N. Danforth, S. Colla, S. Kornbluth, and R. Winfree, 2011: Climate-associated phenological advances in bee pollinators and bee-pollinated plants. *Proceedings of the National Academy of Sciences of the United States of America*, **108(51)**, 20645-20649.

Bateman, B.L., J. VanDerWal, S.E. Williams, and C.N. Johnson, 2012: Biotic interactions influence the projected distribution of a specialist mammal under climate change. *Diversity and Distributions*, **18(9)**, 861-872.

Bateman, B.L., H.T. Murphy, A.E. Reside, K. Mokany, and J. VanDerWal, 2013: Appropriateness of full-, partial- and no-dispersal scenarios in climate change impact modelling. *Diversity and Distributions*, **19(10)**, 1224-1234.

Bathiany, S., M. Claussen, V. Brovkin, T. Raddatz, and V. Gayler, 2010: Combined biogeophysical and biogeochemical effects of large-scale forest cover changes in the MPI earth system model. *Biogeosciences*, **7(5)**, 1383-1399.

Battarbee, R.W., M. Kernan, and N. Rose, 2009: Threatened and stressed mountain lakes of Europe: assessment and progress. *Aquatic Ecosystem Health & Management*, **12(2)**, 118-128.

Beale, C.M. and J.J. Lennon, 2012: Incorporating uncertainty in predictive species distribution modelling. *Philosophical Transactions of the Royal Society B*, **367(1586)**, 247-258.

Beaumont, L.J., A. Pitman, S. Perkins, N.E. Zimmermann, N.G. Yoccoz, and W. Thuiller, 2011: Impacts of climate change on the world's most exceptional ecoregions. *Proceedings of the National Academy of Sciences of the United States of America*, **108(6)**, 2306-2311.

Beck, H.E., T.R. McVicar, A.I.L. van Dijk, J. Schellenkens, R.A.M. de Jeu, and L.A. Bruijinzeel, 2011: Global evaluation of four AVHRR-NDVI data sets: intercomparison and assessment against Landsat imagery. *Remote Sensing of Environment*, **115(10)**, 2547-2563.

Beck, P.S.A. and S.J. Goetz, 2011: Satellite observations of high northern latitude vegetation productivity changes between 1982 and 2008: ecological variability and regional differences. *Environmental Research Letters*, **6(4)**, 045501, doi:10.1088/1748-9326/6/4/045501.

Beck, P.S.A., G.P. Juday, A. Claire, W. Steve, S. Emily, H. Patricia, D.H. James, and S.J. Goetz, 2011: Changes in forest productivity across Alaska are captured in satellite and tree ring records. *Ecology Letters*, **14(4)**, 373-379.

Beerling, D.J. and C.P. Osborne, 2006: The origin of the savanna biome. *Global Change Biology*, **12(11)**, 2023-2031.

Beier, C., I.K. Schmidt, and H.L. Kristensen, 2004: Effects of climate and ecosystem disturbances on biogeochemical cycling in a semi-natural terrestrial ecosystem. *Water, Air and Soil Pollution: Focus*, **4**, 191-206.

Beier, C., B.A. Emmett, J. Penuelas, I.K. Schmidt, A. Tietema, M. Estiarte, P. Gundersen, L. Llorens, T. Riis-Nielsen, A. Sowerby, and A. Gorissen, 2008: Carbon and nitrogen cycles in European ecosystems respond differently to global warming. *Science of the Total Environment*, **407(1)**, 692-697.

Beilman, D.W., G.M. MacDonald, L.C. Smith, and P.J. Reimer, 2009: Carbon accumulation in peatlands of West Siberia over the last 2000 years. *Global Biogeochemical Cycles*, **23(1)**, GB1012, doi:10.1029/2007GB003112.

Bell, G., 2013: Evolutionary rescue and the limits of adaptation. *Philosophical Transactions of the Royal Society B*, **368(1610)**, 20120080, doi:10.1098/rstb.2012.0080.

Bell, G. and A. Gonzalez, 2009: Evolutionary rescue can prevent extinction following environmental change. *Ecology Letters*, **12(9)**, 942-948.

Bellard, C., C. Bertelsmeier, P. Leadley, W. Thuiller, and F. Courchamp, 2012: Impacts of climate change on the future of biodiversity. *Ecology Letters*, **15(4)**, 365-377.

Bellard, C., W. Thuiller, B. Leroy, P. Genovesi, M. Bakkenes, and F. Courchamp, 2013: Will climate change promote future invasions? *Global Change Biology*, **19(12)**, 3740-3748.

Bellassen, V., N. Viovy, S. Luyssaert, G. Le Maire, M.J. Schelhaas, and P. Ciais, 2011: Reconstruction and attribution of the carbon sink of European forests between 1950 and 2000. *Global Change Biology*, **17(11)**, 3274-3292.

Belyazid, S., D. Kurz, S. Braun, H. Sverdrup, B. Rihm, and J.P. Hettelingh, 2011: A dynamic modelling approach for estimating critical loads of nitrogen based on pliant community changes under a changing climate. *Environmental Pollution*, **159(3)**, 789-801.

Bentz, B.J., J. Régnière, C.J. Fettig, E.M. Hansen, J.L. Hayes, J.A. Hicke, R.G. Kelsey, J.F. Negrón, and S.J. Seybold, 2010: Climate change and bark beetles of the Western United States and Canada: direct and indirect effects. *Bioscience*, **60(8)**, 602-613.

Berg, M.P., E.T. Kiers, G. Driessen, M. Van Der Heijden, B.W. Kooi, F. Kuenen, M. Liefting, H.A. Verhoef, and J. Ellers, 2010: Adapt or disperse: understanding species persistence in a changing world. *Global Change Biology*, **16(2)**, 587-598.

Bergeron, Y., D. Cyr, M.P. Girardin, and C. Carcaillet, 2010: Will climate change drive 21st century burn rates in Canadian boreal forest outside of its natural variability: collating global climate model experiments with sedimentary charcoal data. *International Journal of Wildland Fire*, **19(8)**, 1127-1139.

Bergström, A.K. and M. Jansson, 2006: Atmospheric nitrogen deposition has caused nitrogen enrichment and eutrophication of lakes in the northern hemisphere. *Global Change Biology*, **12**, 635-643.

Berkes, F., J. Colding, and C. Folke (eds.), 2003: *Navigating Social-Ecological Systems. Building Resilience for Complexity and Change*. Cambridge University Press, Cambridge, UK, 393 pp.

Bernacchi, C.J., A.D.B. Leakey, L.E. Heady, P.B. Morgan, F.G. Dohleman, J.M. McGrath, K.M. Gillespie, V.E. Wittig, A. Rogers, S.P. Long, and D.R. Ort, 2006: Hourly and seasonal variation in photosynthesis and stomatal conductance of soybean grown at future CO_2 and ozone concentrations for 3 years under fully open-air field conditions. *Plant Cell and Environment*, **29(11)**, 2077-2090.

Bernhardt, E.L., T.N. Hollingsworth, and F.S. Chapin III, 2011: Fire severity mediates climate-driven shifts in understorey community composition of black spruce stands of interior Alaska. *Journal of Vegetation Science*, **22(1)**, 32-44.

Bertaux, D., D. Reale, A.G. McAdam, and S. Boutin, 2004: Keeping pace with fast climate change: can Arctic life count on evolution? *Integrative and Comparitive Biology*, **44(2)**, 140-151.

Bertelsmeier, C., G. Luque, and F. Courchamp, 2012: Global warming may freeze the invasion of big-headed ants. *Biological Invasions*, **15(7)**, 1561-1572.

Bertrand, R., J. Lenoir, C. Piedallu, G. Riofrio-Dillon, P. de Ruffray, C. Vidal, J.C. Pierrat, and J.C. Gegout, 2011: Changes in plant community composition lag behind climate warming in lowland forests. *Nature*, **479(7374)**, 517-520.

Bertzky, M., B. Dickson, R. Galt, E. Glen, M. Harley, N. Hodgson, G. Keder, I. Lysenko, M. Pooley, C. Ravilious, T. Sajwaj, R. Schiopu, Y. de Soye, and G. Tucker, 2010: *Impacts of Climate Change and Selected Renewable Energy Infrastructures on EU Biodiversity and the Natura 2000 Network. Summary Report.* European Commission and International Union for Conservation of Nature, Brussels. http://ec.europa.eu/environment/nature/climatechange/pdf/study.pdf.

Betts, R.A., N.W. Arnell, P. Boorman, S.E. Cornell, J.I. House, N.R. Kaye, M.P. McCarthy, D. McNeall, M.G. Sanderson, and A.J. Wiltshire, 2012: Climate change impacts and adaptation: an earth system view. In: *Understanding the Earth System: Global Change Science for Application* [Cornell, S., C. Prentice, J. House, and C. Downy (eds.)]. Cambridge University Press, Cambridge, UK, pp. 160-201.

Betts, R.A., N. Golding, P. Gonzalez, J. Gornall, R. Kahana, G. Kay, L. Mitchell, and A. Wiltshire, 2013: Climate and land use change impacts on global terrestrial ecosystems, fire, and river flows in the HadGEM2-ES Earth System Model using the Representative Concentration Pathways. *Biogeosciences Discussions*, **10**, 6171-6223. doi:10.5194/bgd-10-6171-2013.

Bhatt, U.S., D.A. Walker, M.K. Raynolds, J.C. Comiso, H.E. Epstein, G.S. Jia, R. Gens, J.E. Pinzon, C.J. Tucker, C.E. Tweedie, and P.J. Webber, 2010: Circumpolar Arctic tundra vegetation change is linked to sea ice decline. *Earth Interactions*, **14**, 8, doi:10.1175/2010EI315.1.

Biesmeijer, J.C., S.P.M. Roberts, M. Reemer, R. Ohlemuller, M. Edwards, T. Peeters, A.P. Schaffers, S.G. Potts, R. Kleukers, C.D. Thomas, J. Settele, and W.E. Kunin, 2006: Parallel declines in pollinators and insect-pollinated plants in Britain and The Netherlands. *Science*, **313(5785)**, 351-354.

Biggs, D., R. Biggs, V. Dakos, R.J. Scholes, and M. Schoon, 2011: Are we entering an era of concatenated global crises? *Ecology and Society*, **16(2)**, 27, www.ecology andsociety.org/vol16/iss2/art27/.

Biggs, R., S.R. Carpenter, and W.A. Brock, 2009: Turning back from the brink: detecting an impending regime shift in time to avert it. *Proceedings of the National Academy of Sciences of the United States of America*, **106(3)**, 826-831.

Birdsey, R.A., K.S. Pregitzer, and A. Lucier, 2006: Forest carbon management in the United States: 1600-2100. *Journal of Environmental Quality*, **35(4)**, 1461-1469.

Bleeker, A., W.K. Hicks, E. Dentener, J. Galloway, and J.W. Erisman, 2011: N deposition as a threat to the World's protected areas under the Convention on Biological Diversity. *Environmental Pollution*, **159(10)**, 2280-2288.

Blok, D., M.M.P.D. Heijmans, G. Schaepman-Strub, A.V. Kononov, T.C. Maximov, and F. Berendse, 2010: Shrub expansion may reduce summer permafrost thaw in Siberian tundra. *Global Change Biology*, **16(4)**, 1296-1305.

Bloor, J., P. Pichon, R. Falcimagne, P. Leadley, and J.-F. Soussana, 2010: Effects of warming, summer drought, and CO_2 enrichment on aboveground biomass production, flowering phenology, and community structure in an upland grassland ecosystem. *Ecosystems*, **13(6)**, 888-900.

BMT WBM, 2010: *Kakadu – Vulnerability to Climate Change Impacts.* A report to the Australian Government Department of Climate Change and Energy Efficiency. Australian Government, Department of Climate Change and Energy Efficiency, Canberra, ACT, Australia, 226 pp.

Bobbink, R., K. Hicks, J. Galloway, T. Spranger, R. Alkemade, M. Ashmore, M. Bustamante, S. Cinderby, E. Davidson, F. Dentener, B. Emmett, J.W. Erisman, M. Fenn, F. Gilliam, A. Nordin, L. Pardo, and W. De Vries, 2010: Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis. *Ecological Applications*, **20(1)**, 30-59.

Bockheim, J., G. Vieira, M. Ramos, J. Lopez-Martinez, E. Serrano, M. Guglielmin, K. Wilhelm, and A. Nieuwendam, 2013: Climate warming and permafrost dynamics in the Antarctic Peninsula region. *Global and Planetary Change*, **100**, 215-223.

Boggs, C.L. and D.W. Inouye, 2012: A single climate driver has direct and indirect effects on insect population dynamics. *Ecology Letters*, **15(5)**, 502-508.

Boisvenue, C. and S.W. Running, 2006: Impacts of climate change on natural forest productivity - evidence since the middle of the 20th century. *Global Change Biology*, **12(5)**, 862-882.

Bolte, A. and B. Degen, 2010: Forest adaptation to climate change – options and limitations. *Landbauforschung*, **60(3)**, 111-117.

Bolte, A., C. Ammer, M. Lof, P. Madsen, G.J. Nabuurs, P. Schall, P. Spathelf, and J. Rock, 2009: Adaptive forest management in central Europe: Climate change impacts, strategies and integrative concept. *Scandinavian Journal of Forest Research*, **24(6)**, 473-482.

Bolte, A., L. Hilbrig, B. Grundmann, F. Kampf, J. Brunet, and A. Roloff, 2010: Climate change impacts on stand structure and competitive interactions in a southern Swedish spruce-beech forest. *European Journal of Forest Research*, **129(3)**, 261-276.

Bomhard, B., D.M. Richardson, J.S. Donaldson, G.O. Hughes, G.F. Midgley, D.C. Raimondo, A.G. Rebelo, M. Rouget, and W. Thuiller, 2005: Potential impacts of future land use and climate change on the Red List status of the Proteaceae in the Cape Floristic Region, South Africa. *Global Change Biology*, **11(9)**, 1452-1468.

Bonan, G.B., 2008: Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science*, **320(5882)**, 1444-1449.

Bond, N.R., P.S. Lake, and A.H. Arthington, 2008: The impacts of drought on freshwater ecosystems: an Australian perspective. *Hydrobiologia*, **600(1)**, 3-16.

Bond, W.J. and J.J. Midgley, 2001: Ecology of sprouting in woody plants: the persistence niche. *Trends in Ecology & Evolution*, **16(1)**, 45-51.

Bond, W.J. and G.F. Midgley, 2012: Carbon dioxide and the uneasy interactions of trees and savannah grasses. *Philosophical Transactions of the Royal Society B*, **367(1588)**, 601-612.

Bond-Lamberty, B. and A. Thomson, 2010: Temperature-associated increases in the global soil respiration record. *Nature*, **464(7288)**, 579-582.

Bond-Lamberty, B., S.D. Peckham, D.E. Ahl, and S.T. Gower, 2007: Fire as the dominant driver of central Canadian boreal forest carbon balance. *Nature*, **450(7166)**, 89-92.

Bonfils, C.J.W., T.J. Phillips, D.M. Lawrence, P. Cameron-Smith, W.J. Riley, and Z.M. Subin, 2012: On the influence of shrub height and expansion on northern high latitude climate. *Environmental Research Letters*, **7(1)**, 015503, doi:10.1088/1748-9326/7/1/015503.

Bontemps, J.D., J.C. Herve, J.M. Leban, and J.F. Dhote, 2011: Nitrogen footprint in a long-term observation of forest growth over the twentieth century. *Trees – Structure and Function*, **25(2)**, 237-251.

Booker, K., L. Huntsinger, J.W. Bartolome, N.F. Sayre, and W. Stewart, 2013: What can ecological science tell us about opportunities for carbon sequestration on arid rangelands in the United States? *Global Environmental Change: Human and Policy Dimensions*, **23(1)**, 240-251.

Booth, R.K., S.T. Jackson, S.L. Forman, J.E. Kutzbach, E.A. Bettis, J. Kreig, and D.K. Wright, 2005: A severe centennial-scale drought in mid-continental North America 4200 years ago and apparent global linkages. *Holocene*, **15(3)**, 321-328.

Bosio, J., M. Johansson, T.V. Callaghan, B. Johansen, and T.R. Christensen, 2012: Future vegetation changes in thawing subarctic mires and implications for greenhouse gas exchange – a regional assessment. *Climatic Change*, **115(2)**, 379-398.

Both, C., S. Bouwhuis, C.M. Lesselis, and M.E. Visser, 2006: Climate change and population declines in a long-distance migratory bird. *Nature*, **441(7089)**, 81-83.

Both, C., C.A.M. Van Turnhout, R.G. Bijlsma, H. Siepel, A.J. Van Strien, and R.P.B. Foppen, 2010: Avian population consequences of climate change are most severe for long-distance migrants in seasonal habitats. *Proceedings of the Royal Society B*, **277(1685)**, 1259-1266.

Botkin, D.B., H. Saxe, M.B. Araujo, R. Betts, R.H.W. Bradshaw, T. Cedhagen, P. Chesson, T.P. Dawson, J.R. Etterson, D.P. Faith, S. Ferrier, A. Guisan, A.S. Hansen, D.W. Hilbert, C. Loehle, C. Margules, M. New, M.J. Sobel, and D.R.B. Stockwell, 2007: Forecasting the effects of global warming on biodiversity. *BioScience*, **57(3)**, 227-236.

Boutton, T.W., J.D. Liao, T.R. Filley, and S.R. Archer, 2009: Belowground carbon storage and dynamics accompanying woody plant encroachment in a subtropical savanna. *Soil Carbon Sequestration and the Greenhouse Effect* [Lal, R. and R. Follett (eds.)]. 2nd edn., Soil Science Society of America, Inc., Madison, WI, USA, pp. 181-205.

Bowman, D., J.K. Balch, P. Artaxo, W.J. Bond, J.M. Carlson, M.A. Cochrane, C.M. D'Antonio, R.S. DeFries, J.C. Doyle, S.P. Harrison, F.H. Johnston, J.E. Keeley, M.A. Krawchuk, C.A. Kull, J.B. Marston, M.A. Moritz, I.C. Prentice, C.I. Roos, A.C. Scott, T.W. Swetnam, G.R. van der Werf, and S.J. Pyne, 2009: Fire in the Earth system. *Science*, **324(5926)**, 481-484.

Bowman, D.M.J.S., B.P. Murphy, and D.S. Banfai, 2011: Has global environmental change caused monsoon rainforests to expand in the Australian monsoon tropics? *Landscape Ecology*, **25(8)**, 1247-1260.

Bradley, B.A., M. Oppenheimer, and D.S. Wilcove, 2009: Climate change and plant invasions: restoration opportunities ahead? *Global Change Biology*, **15(6)**, 1511-1521.

Bradley, B.A., D.M. Blumenthal, D.S. Wilcove, and L.H. Ziska, 2010: Predicting plant invasions in an era of global change. *Trends in Ecology & Evolution*, **25(5)**, 310-318.

Brandão, R.A. and A.F.B. Araújo, 2007: Changes in anuran species richness and abundance resulting from hydroelectric dam flooding in central Brazil. *Biotropica*, **40(2)**, 263-266.

Brando, P.M., S.J. Goetz, A. Baccini, D.C. Nepstad, P.S.A. Beck, and M.C. Christman, 2010: Seasonal and interannual variability of climate and vegetation indices across the Amazon. *Proceedings of the National Academy of Sciences of the United States of America*, **107(33)**, 14685-14690.

Brando, P.M., D.C. Nepstad, J.K. Balch, B. Bolker, M.C. Christman, M.T. Coe, and F.E. Putz, 2012: Fire-induced tree mortality in a neotropical forest: the roles of bark traits, tree size, wood density and fire behavior. *Global Change Biology*, **18(2)**, 630-641.

Brasier, C. and J. Webber, 2010: Plant pathology: Sudden larch death. *Nature*, **466(7308)**, 824-825.

Breshears, D.D., 2006: The grassland-forest continuum: trends in ecosystem properties for woody plant mosaics? *Frontiers in Ecology and the Environment*, **4(2)**, 96-104.

Breshears, D.D., N.S. Cobb, P.M. Rich, K.P. Price, C.D. Allen, R.G. Balice, W.H. Romme, J.H. Kastens, M.L. Floyd, J. Belnap, J.J. Anderson, O.B. Myers, and C.W. Meyer, 2005: Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Sciences of the United States of America*, **102(42)**, 15144-15148.

Bridle, J.R., J. Polechova, M. Kawata, and R.K. Butlin, 2010: Why is adaptation prevented at ecological margins? New insights from individual-based simulations. *Ecology Letters*, **13(4)**, 485-494.

Briffa, K.R., V.V. Shishov, T.M. Melvin, E.A. Vaganov, H. Grudd, R.M. Hantemirov, M. Eronen, and M.M. Naurzbaev, 2008: Trends in recent temperature and radial tree growth spanning 2000 years across northwest Eurasia. *Philosophical Transactions of the Royal Society B*, **363(1501)**, 2271-2284.

Brink, V.C., 1959: A directional change in the subalpine forest-heath ecotone in Garibaldi Park, British Columbia. *Ecology*, **40(1)**, 10-16.

Brisson, J., S. de Blois, and C. Lavoie, 2010: Roadside as invasion pathway for common reed (Phragmites australis). *Invasive Plant Science and Management*, **3(4)**, 506-514.

Brittain, C., R. Bommarco, M. Vighi, S. Barmaz, J. Settele, and S.G. Potts, 2010a: The impact of an insecticide on insect flower visitation and pollination in an agricultural landscape. *Agricultural and Forest Entomology*, **12(3)**, 259-266.

Brittain, C.A., M. Vighi, R. Bommarco, J. Settele, and S.G. Potts, 2010b: Impacts of a pesticide on pollinator species richness at different spatial scales. *Basic and Applied Ecology*, **11(2)**, 106-115.

Britton, A.J., C.M. Beale, W. Towers, and R.L. Hewison, 2009: Biodiversity gains and losses: Evidence for homogenisation of Scottish alpine vegetation. *Biological Conservation*, **142(8)**, 1728-1739.

Britton, J.R., J. Cucherousset, G.D. Davies, M.J. Godard, and G.H. Copp, 2010: Non-native fishes and climate change: predicting species responses to warming emperatures in a temperate region. *Freshwater Biology*, **55(5)**, 1130-1141.

Broadmeadow, M.S.J., D. Ray, and C.J.A. Samuel, 2005: Climate change and the future for broadleaved tree species in Britain. *Forestry*, **78(2)**, 145-161.

Broennimann, O., U.A. Treier, H. Muller-Scharer, W. Thuiller, A.T. Peterson, and A. Guisan, 2007: Evidence of climatic niche shift during biological invasion. *Ecology Letters*, **10(8)**, 701-709.

Brommer, J.E., A. Lehikoinen, and J. Valkama, 2012: The breeding ranges of central European and Arctic bird species move poleward. *PLoS One*, **7(9)**, e43648, doi:10.1371/journal.pone.0043648.

Bronson, D.R., S.T. Gower, M. Tanner, and I. Van Herk, 2009: Effect of ecosystem warming on boreal black spruce bud burst and shoot growth. *Global Change Biology*, **15(6)**, 1534-1543.

Brook, B.W., 2008: Synergies between climate change, extinctions and invasive vertebrates. *Wildlife Research*, **35(3)**, 249-252.

Brook, B.W. and D.M.J.S. Bowman, 2006: Postcards from the past: charting the landscape-scale conversion of tropical Australian savanna to closed forest during the 20th century. *Landscape Ecology*, **21(8)**, 1253-1266.

Brook, B.W., N.S. Sodhi, and C.J.A. Bradshaw, 2008: Synergies among extinction drivers under global change. *Trends in Ecology & Evolution*, **23(8)**, 453-460.

Brook, B.W., E.C. Ellis, M.P. Perring, A.W. Mackay, and L. Blomqvist, 2013: Does the terrestrial biosphere have planetary tipping points? *Trends in Ecology & Evolution*, **28(7)**, 396-401.

Brouwers, N., J. Mercer, T. Lyons, P. Poot, E. Veneklaas, and G. Hardy, 2012: Climate and landscape drivers of tree decline in a Mediterranean ecoregion. *Ecology and Evolution*, **3(1)**, 67-79.

Brouwers, N., G. Matusick, K. Ruthrof, T. Lyons, and G. Hardy, 2013: Landscape-scale assessment of tree crown dieback following extreme drought and heat in a Mediterranean eucalypt forest ecosystem. *Landscape Ecology*, **28(1)**, 69-80.

Brovkin, V., L. Boysen, T. Raddatz, V. Gayler, A. Loew, and M. Claussen, 2013: Evaluation of vegetation cover and land-surface albedo in MPI-ESM CMIP5 simulations. *Journal of Advances in Modeling Earth Systems*, **5(1)**, 48-57.

Brown, C.D., 2010: Tree-line dynamics: adding fire to climate change prediction. *Arctic*, **63(4)**, 488-492.

Brown, L.E., D.M. Hannah, and A.M. Milner, 2007: Vulnerability of alpine stream biodiversity to shrinking glaciers and snowpacks. *Global Change Biology*, **13(5)**, 958-966.

Brusca, R.C., J.F. Wiens, W.M. Meyer, J. Eble, K. Franklin, J.T. Overpeck, and M.W., 2013: Dramatic response to climate change in the Southwest: Robert Whittaker's 1963 Arizona Mountain plant transect revisited. *Ecology and Evolution*, **3(10)**, 3307-3319.

Bryant, M.D., 2009: Global climate change and potential effects on Pacific salmonids in freshwater ecosystems of southeast Alaska. *Climatic Change*, **95(1-2)**, 169-193.

Buckley, J., R.K. Butlin, and J.R. Bridle, 2012: Evidence for evolutionary change associated with the recent range expansion of the British butterfly, *Aricia agestis*, in response to climate change. *Molecular Ecology*, **21(2)**, 267-280.

Buckley, L.B., M.C. Urban, M.J. Angilletta, L.G. Crozier, L.J. Rissler, and M.W. Sears, 2010: Can mechanism inform species' distribution models? *Ecology Letters*, **13(8)**, 1041-1054.

Buongiorno, J., R. Raunikar, and S. S. A. Zhu, 2011: Consequences of increasing bioenergy demand on wood and forests: An application of the Global Forest Products Model. *Journal of Forest Economics*, **17(2)**, 214-229.

Buisson, L. and G. Grenouillet, 2009: Contrasted impacts of climate change on stream fish assemblages along an environmental gradient. *Diversity and Distributions*, **15(4)**, 613-626.

Buisson, L., W. Thuiller, S. Lek, P. Lim, and G. Grenouillet, 2008: Climate change hastens the turnover of stream fish assemblages. *Global Change Biology*, **14(10)**, 2232-2248.

Buitenwerf, R., W.J. Bond, N. Stevens, and W.W. Trollope, 2012: Increased tree densities in two South African savannas: > 50 years of data suggests CO_2 as a driver. *Global Change Biology*, **18(2)**, 675-684.

Bunn, S.E. and A.H. Arthington, 2002: Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management*, **30(4)**, 492-507.

Burgmer, T., H. Hillebrand, and M. Pfenninger, 2007: Effects of climate-driven temperature changes on the diversity of freshwater macroinvertebrates. *Oecologia*, **151(1)**, 93-103.

Burkhead, N.M., 2012: Extinction rates in North American freshwater fishes, 1900-2010. *BioScience*, **62(9)**, 798-808.

Burkle, L.A., J.C. Marlin, and T.M. Knight, 2013: Plant-pollinator interactions over 120 Years: loss of species, co-occurrence, and function. *Science*, **339(6127)**, 1611-1615.

Burrows, M.T., D.S. Schoeman, L.B. Buckley, P. Moore, E.S. Poloczanska, K.M. Brander, C. Brown, J.F. Bruno, C.M. Duarte, B.S. Halpern, J. Holding, C.V. Kappel, W. Kiessling, M.I. O'Connor, J.M. Pandolfi, C. Parmesan, F.B. Schwing, W.J. Sydeman, and A.J. Richardson, 2011: The pace of shifting climate in marine and terrestrial ecosystems. *Science*, **334(6056)**, 652-655.

Burton, O.J., B.L. Phillips, and J.M.J. Travis, 2010: Trade-offs and the evolution of life-histories during range expansion. *Ecology Letters*, **13(10)**, 1210-1220.

Bustamante, H.M., L.J. Livo, and C. Carey, 2010: Effects of temperature and hydric environment on survival of the Panamanian Golden Frog infected with a pathogenic chytrid fungus. *Integrative Zoology*, **5(2)**, 143-153.

Buswell, J.M., A.T. Moles, and S. Hartley, 2011: Is rapid evolution common in introduced plant species? *Journal of Ecology*, **99(1)**, 214-224.

Bütof, A., L.R. von Riedmatten, C.F. Dormann, M. Scherer-Lorenzen, E. Welk, and H. Bruelheide, 2012: The responses of grassland plants to experimentally simulated climate change depend on land use and region. *Global Change Biology*, **18(1)**, 127-137.

Butt, N., P.A. de Oliveira, and M.H. Costa, 2011: Evidence that deforestation affects the onset of the rainy season in Rondonia, Brazil. *Journal of Geophysical Research: Atmospheres*, **116(D11)**, D11120, doi:10.1029/2010JD015174.

Cabral, A.C., J.M. Miguel, A.J. Rescia, M.F. Schmitz, and F.D. Pineda, 2009: Shrub encroachment in Argentinean savannas. *Journal of Vegetation Science*, **14(2)**, 145-152.

Cadotte, M.W., 2006: Dispersal and species diversity: a meta-analysis. *American Naturalist*, **167(6)**, 913-924.

Caesar, J., E. Palin, S. Liddicoat, J. Lowe, E. Burke, A. Pardaens, M. Sanderson, and R. Kahana, 2013: Response of the HadGEM2 Earth System Model to future greenhouse gas emissions pathways to the year 2300. *Journal of Climate*, **26(10)**, 3275-3284.

Cahill, A.E., M.E. Aiello-Lammens, M.C. Fisher-Reid, X. Hua, C.J. Karanewsky, H.Y. Ryu, G.C. Sbeglia, F. Spagnolo, J.B. Waldron, O. Warsi, and J.J. Wiens, 2013: How does climate change cause extinction? *Proceedings of the Royal Society B*, **280(1750)**, 20121890, doi:10.1098/rspb.2012.1890.

Cailleret, M., M. Nourtier, A. Amm, M. Durand-Gillmann, and H. Davi, 2013: Drought-induced decline and mortality of silver fir differ among three sites in Southern France. *Annals of Forest Science*, doi:10.1007/s13595-013-0265-0.

Caissie, D., 2006: The thermal regime of rivers: a review. *Freshwater Biology*, **51(8)**, 1389-1406.

Caldow, R.W.G., R.A. Stillman, S.E.A. le V. dit Durell, A.D. West, S. McGrorty, J.D. Goss-Custard, P.J. Wood, and J. Humphreys, 2007: Benefits to shorebirds from invasion of a non-native shellfish. *Proceedings of the Royal Society B*, **274(1616)**, 1449-1455.

Cameron, A., 2012: Refining risk estimates using models. In: *Saving a Million Species: Extinction Risk from Climate Change* [Hannah, L. (ed.)]. Island Press, Washington, DC, USA, pp. 41-72.

Canadell, J.G. and M.R. Raupach, 2008: Managing forests for climate change mitigation. *Science*, **320(5882)**, 1456-1457.

Canadell, J.G., C. Le Quéré, M.R. Raupach, C.B. Field, E.T. Buitenhuis, P. Ciais, T.J. Conway, N.P. Gillett, R.A. Houghton, and G. Marland, 2007: Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the National Academy of Sciences of the United States of America*, **104(47)**, 18866-18870.

Canfield, D.E., A.N. Glazer, and P.G. Falkowski, 2010: The evolution and future of Earth's nitrogen cycle. *Science*, **330(6001)**, 192-196.

Cannone, N., S. Sgorbati, and M. Guglielmin, 2007: Unexpected impacts of climate change on alpine vegetation. *Frontiers in Ecology and the Environment*, **5(7)**, 360-364.

Cannone, N., G. Diolaiuti, M. Guglielmin, and C. Smiraglia, 2008: Accelerating climate change impacts on alpine glacier forefield ecosystems in the European Alps. *Ecological Applications*, **18(3)**, 637-648.

Capon, S.J., 2007: Effects of flooding on seedling emergence from the soil seed bank of a large desert floodplain. *Wetlands*, **27(4)**, 904-914.

Capon, S.J., L.E. Chambers, R. Mac Nally, R.J. Naiman, P. Davies, N. Marshall, J. Pittock, M. Reid, T. Capon, M. Douglas, J. Catford, D.S. Baldwin, M. Stewardson, J. Roberts, M. Parsons, and S.E. Williams, 2013: Riparian ecosystems in the 21st century: hotspots for climate change adaptation? *Ecosystems*, **16(3)**, 359-381.

Carmo, J.B.d., E.R. de Sousa Neto, P.J. Duarte-Neto, J.P.H.B. Ometto, and L.A. Martinelli, 2012: Conversion of the coastal Atlantic forest to pasture: Consequences for the nitrogen cycle and soil greenhouse gas emissions. *Agriculture, Ecosystems & Environment*, **148(0)**, 37-43.

Carnicer, J., M. Coll, M. Ninyerola, X. Pons, G. Sanchez, and J. Penuelas, 2011: Widespread crown condition decline, food web disruption, and amplified tree mortality with increased climate change-type drought. *Proceedings of the National Academy of Sciences of the United States of America*, **108(4)**, 1474-1478.

Cavagnaro, T.R., R.M. Gleadow, and R.E. Miller, 2011: Plant nutrient acquisition and utilisation in a high carbon dioxide world. *Functional Plant Biology*, **38(2)**, 87-96.

CBD, 2012: *Geoengineering in Relation to the Convention on Biological Diversity: Technical and Regulatory Matters.* CBD Technical Series Series 66, Secretariat of the Convention on Biological Diversity, Montreal, Cannada, 152 pp.

Chapin III, F.S., M. Sturm, M.C. Serreze, J.P. McFadden, J.R. Key, A.H. Lloyd, A.D. McGuire, T.S. Rupp, A.H. Lynch, J.P. Schimel, J. Beringer, W.L. Chapman, H.E. Epstein, E.S. Euskirchen, L.D. Hinzman, G. Jia, C.L. Ping, K.D. Tape, C.D.C. Thompson, D.A. Walker, and J.M. Welker, 2005: Role of land-surface changes in Arctic summer warming. *Science*, **310(5748)**, 657-660.

Charru, M., I. Seynave, F. Morneau, and J.D. Bontemps, 2010: Recent changes in forest productivity: an analysis of national forest inventory data for common beech (*Fagus sylvatica* L.) in north-eastern France. *Forest Ecology and Management*, **260(5)**, 864-874.

Chaturvedi, R.K., R. Gopalakrishnan, M. Jayaraman, G. Bala, N.V. Joshi, R. Sukumar, and N.H. Ravindranath, 2011: Impact of climate change on Indian forests: a dynamic vegetation modeling approach. *Mitigation and Adaptation Strategies for Global Change*, **16(2)**, 119-142.

Cheaib, A., V. Badeau, J. Boe, I. Chuine, C. Delire, E. Dufrêne, C. François, E.S. Gritti, M. Legay, C. Pagé, W. Thuiller, N. Viovy, and P. Leadley, 2012: Climate change impacts on tree ranges: model intercomparison facilitates understanding and quantification of uncertainty. *Ecology Letters*, **15(6)**, 533-544.

Chen, I.-C., H.J. Shiu, S. Benedick, J.D. Holloway, V.K. Cheye, H.S. Barlow, J.K. Hill, and C.D. Thomas, 2009: Elevation increases in moth assemblages over 42 years on a tropical mountain. *Proceedings of the National Academy of Sciences of the United States of America*, **106(5)**, 1479-1483.

Chen, I.-C., J.K. Hill, R. Ohlemüller, D.B. Roy, and C.D. Thomas, 2011: Rapid range shifts of species associated with high levels of climate warming. *Science*, **333(6045)**, 1024-1026.

Chessman, B.C., 2009: Climatic changes and 13-year trends in stream macroinvertebrate assemblages in New South Wales, Australia. *Global Change Biology*, **15(11)**, 2791-2802.

Chevin, L.M., R. Lande, and G.M. Mace, 2010: Adaptation, plasticity, and extinction in a changing environment: towards a predictive theory. *PLoS Biology*, **8(4)**, e1000357, doi:10.1371/journal.pbio.1000357.

Chiba, S. and K. Roy, 2011: Selectivity of terrestrial gastropod extinctions on an oceanic archipelago and insights into the anthropogenic extinction process. *Proceedings of the National Academy of Sciences of the United States of America*, **108(23)**, 9496-9501.

Chisholm, R.A., 2010: Trade-offs between ecosystem services: Water and carbon in a biodiversity hotspot. *Ecological Economics*, **69(10)**, 1973-1987.

Chmura, D.J., P.D. Anderson, G.T. Howe, C.A. Harrington, J.E. Halofsky, D.L. Peterson, D.C. Shaw, and J.B. St. Clair, 2011: Forest responses to climate change in the northwestern United States: ecophysiological foundations for adaptive management. *Forest Ecology and Management*, **261(7)**, 1121-1142.

Choat, B., S. Jansen, T.J. Brodribb, H. Cochard, S. Delzon, R. Bhaskar, S.J. Bucci, T.S. Feild, S.M. Gleason, U.G. Hacke, A.L. Jacobsen, F. Lens, H. Maherali, J. Martinez-Vilalta, S. Mayr, M. Mencuccini, P.J. Mitchell, A. Nardini, J. Pittermann, R.B. Pratt, J.S. Sperry, M. Westoby, I.J. Wright, and A.E. Zanne, 2012: Global convergence in the vulnerability of forests to drought. *Nature*, **491(7426)**, 752-755.

Chown, S.L., A.A. Hoffmann, T.N. Kristensen, M.J. Angilletta, N.C. Stenseth, and C. Pertoldi, 2010: Adapting to climate change: a perspective from evolutionary physiology. *Climate Research*, **43(1-2)**, 3-15.

Chown, S.L., A.H.L. Huiskes, N.J.M. Gremmen, J.E. Lee, A. Terauds, K. Crosbie, Y. Frenot, K.A. Hughes, S. Imura, K. Kiefer, M. Lebouvier, B. Raymond, M. Tsujimoto, C. Ware, B. van den Vijver, and D.M. Bergstrom, 2012: Continent-wide risk assessment for the establishment of nonindigenous species in Antarctica. *Proceedings of the National Academy of Sciences of the United States of America*, **109(13)**, 4938-4943.

Christie, P. and M. Sommerkorn, 2012: *RaCeR: Rapid Assessment of Circum-Arctic Ecosystem Resilience*. WWF Global Arctic Programme, World Wildlife Fund (WWF), Ottawa, Canada, 70 pp.

Chuine, I., X. Morin, L. Sonie, C. Collin, J. Fabreguettes, D. Degueldre, J.L. Salager, and J. Roy, 2012: Climate change might increase the invasion potential of the alien C4 grass *Setaria parviflora* (Poaceae) in the Mediterranean Basin. *Diversity and Distributions*, **18(7)**, 661-672.

Churkina, G., S. Zaehle, J. Hughes, N. Viovy, Y. Chen, M. Jung, B.W. Heumann, N. Ramankutty, M. Heimann, and C. Jones, 2010: Interactions between nitrogen deposition, land cover conversion, and climate change determine the contemporary carbon balance of Europe. *Biogeosciences*, **7(9)**, 2749-2764.

Ciais, P., M. Reichstein, N. Viovy, A. Granier, J. Ogee, V. Allard, M. Aubinet, N. Buchmann, C. Bernhofer, A. Carrara, F. Chevallier, N. De Noblet, A.D. Friend, P. Friedlingstein, T. Grunwald, B. Heinesch, P. Keronen, A. Knohl, G. Krinner, D. Loustau, G. Manca, G. Matteucci, F. Miglietta, J.M. Ourcival, D. Papale, K. Pilegaard, S. Rambal, G. Seufert, J.F. Soussana, M.J. Sanz, E.D. Schulze, T. Vesala, and R. Valentini, 2005: Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature*, **437(7058)**, 529-533.

Ciais, P., M.J. Schelhaas, S. Zaehle, L. Piao, A. Cescatti, J. Liski, S. Luyssaert, G. Le-Maire, E.D. Schulze, O. Bouriaud, A. Freibauer, R. Valentini, and G.J. Nabuurs, 2008: Carbon accumulation in European forests. *Nature Geoscience*, **1(7)**, 425-429.

Clark, C.M. and D. Tilman, 2008: Loss of plant species after chronic low-level nitrogen deposition to prairie grasslands. *Nature*, **451(7179)**, 712-715.

Clark, D.A., S.C. Piper, C.D. Keeling, and D.B. Clark, 2003: Tropical rain forest tree growth and atmospheric carbon dynamics linked to interannual temperature variation during 1984-2000. *Proceedings of the National Academy of Sciences of the United States of America*, **100(10)**, 5852-5857.

Clark, J.S., 1998: Why trees migrate so fast: confronting theory with dispersal biology and the paleorecord. *American Naturalist*, **152(2)**, 204-224.

Clark, P.U., A.S. Dyke, J.D. Shakun, A.E. Carlson, J. Clark, B. Wohlfarth, J.X. Mitrovica, S.W. Hostetler, and A.M. McCabe, 2009: The Last Glacial Maximum. *Science*, **325(5941)**, 710-714.

Clarke, H., C. Lucas, and P. Smith, 2013: Changes in Australian fire weather between 1973 and 2010. *International Journal of Climatology*, **33(4)**, 931-944.

Claussen, M., 2009: Late Quaternary vegetation-climate feedbacks. *Climate of the Past*, **5(2)**, 203-216.

Claussen, M., K. Selent, V. Brovkin, T. Raddatz, and V. Gayler, 2013: Impact of CO_2 and climate on Last Glacial Maximum vegetation – a factor separation. *Biogeosciences*, **10(6)**, 3593-3604.

Clavero, M., D. Villero, and L. Brotons, 2011: Climate change or land use dynamics: Do we know what climate change indicators indicate? *PLoS One*, **6(4)**, e18581, doi:10.1371/journal.pone.0018581.

Cleland, E. and W.S. Harpole, 2010: Nitrogen enrichment and plant communities. *Annals of the New York Academy of Sciences,* **1195(1)**, 46-61.

Cleland, E.E., I. Chuine, A. Menzel, H.A. Mooney, and M.D. Schwartz, 2007: Shifting plant phenology in response to global change. *Trends in Ecology & Evolution*, **22(7)**, 357-365.

Cleland, E.E., J.M. Allen, T.M. Crimmins, J.A. Dunne, S. Pau, S. Travers, E.S. Zavaleta, and E.M. Wolkovich, 2012: Phenological tracking enables positive species responses to climate change. *Ecology*, **93(8)**, 1765-1771.

Clements, D.R. and A. Ditommaso, 2011: Climate change and weed adaptation: can evolution of invasive plants lead to greater range expansion than forecasted? *Weed Research*, **51(3)**, 227-240.

Cobben, M.M.P., J. Verboom, P.F.M. Opdam, R.F. Hoekstra, R. Jochem, and M.J.M. Smulders, 2012: Wrong place, wrong time: climate change-induced range shift across fragmented habitat causes maladaptation and declined population size in a modelled bird species. *Global Change Biology*, **18(8)**, 2419-2428.

Cochrane, M.A., 2003: Fire science for rainforests. *Nature*, **421**, 913-919.

Cochrane, M.A. and C.P. Barber, 2009: Climate change, human land use and future fires in the Amazon. *Global Change Biology*, **15(3)**, 601-612.

Cole, J.J., Y.T. Prairie, N.F. Caraco, W.H. McDowell, L.J. Tranvik, R.G. Striegl, C.M. Duarte, P. Kortelainen, J.A. Downing, J.J. Middelburg, and J. Melack, 2007: Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget. *Ecosystems*, **10(1)**, 171-184.

Collatz, M.H., M. Ribbas-Carbo, and J.A. Berry, 1992: Coupled photosynthesis – stomatal conductances model for leaves of C_4 plants. *Australian Journal of Plant Physiology*, **19**, 519-538.

Collins, J.P., 2010: Amphibian decline and extinction: what we know and what we need to learn. *Diseases of Aquatic Organisms*, **92(2-3)**, 93-99.

Colls, A., N. Ash, and N. Ikkala, 2009: *Ecosystem-based Adaptation: A Natural Response to Climate Change.* International Union for Conservation of Nature and Natural Resources (IUCN), Gland, Switzerland, 16 pp.

Colwell, R.K., G. Brehm, C.L. Cardelus, A.C. Gilman, and J.T. Longino, 2008: Global warming, elevational range shifts, and lowland biotic attrition in the wet tropics. *Science*, **322(5899)**, 258-261.

Comte, L. and G. Grenouillet, 2013: Do stream fish track climate change? Assessing distribution shifts in recent decades. *Ecography*, **36(11)**, 1236-1246.

Comte, L., L. Buisson, M. Daufresne, and G. Grenouillet, 2013: Climate-induced changes in the distribution of freshwater fish: observed and predicted trends. *Freshwater Biology*, **58(4)**, 625-639.

Conlisk, E., D. Lawson, A.D. Syphard, J. Franklin, L. Flint, A. Flint, and H.M. Regan, 2012: The roles of dispersal, fecundity, and predation in the population persistence of an oak (*Quercus engelmannii*) under global change. *PLoS One*, **7(5)**, e36391, doi:10.1371/journal.pone.0036391.

Connell, J.H., 1978: Diversity in tropical rain forests and coral reefs. *Science*, **199(4335)**, 1302-1310.

Cook, B.I., E.R. Cook, P.C. Huth, J.E. Thompson, A. Forster, and D. Smiley, 2008: A cross-taxa phenological dataset from Mohonk Lake, NY and its relationship to climate. *International Journal of Climatology*, **28(10)**, 1369-1383.

Cook, B.I., E.M. Wolkovich, T.J. Davies, T.R. Ault, J.L. Betancourt, J.M. Allen, K. Bolmgren, E.E. Cleland, T.M. Crimmins, N.J.B. Kraft, L.T. Lancaster, S.J. Mazer, G.J. McCabe, B.J. McGill, C. Parmesan, S. Pau, J. Regetz, N. Salamin, M.D. Schwartz, and S.E. Travers, 2012a: Sensitivity of spring phenology to warming across temporal and spatial climate gradients in two independent databases. *Ecosystems*, **15(8)**, 1283-1294.

Cook, B.I., E.M. Wolkovich, and C. Parmesan, 2012b: Divergent responses to spring and winter warming drive community level flowering trends. *Proceedings of the National Academy of Sciences of the United States of America*, **109(23)**, 9000-9005.

Cooper, O.R., D.D. Parrish, A. Stohl, M. Trainer, P. Nedelec, V. Thouret, J.P. Cammas, S.J. Oltmans, B.J. Johnson, D. Tarasick, T. Leblanc, I.S. McDermid, D. Jaffe, R. Gao, S. Stith, T. Ryerson, K. Aikin, T. Campos, A. Weinheimer, and A.M. Avery, 2010: Increasing springtime ozone mixing ratios in the free troposphere over western North America. *Nature*, **463(12)**, 344-348.

Corlett, R.T., 2011: Impacts of warming on tropical lowland rainforests. *Trends in Ecology & Evolution*, **26(11)**, 606-613.

Costa, M.H., S.N.M. Yanagi, P. Souza, A. Ribeiro, and E.J.P. Rocha, 2007: Climate change in Amazonia caused by soybean cropland expansion, as compared to caused by pastureland expansion. *Geophysical Research Letters*, **34(7)**, L07706, doi:10.1029/2007GL029271.

Cox, P.M., C. Huntingford, and R.J. Harding, 1998: A canopy conductance and photosynthesis model for use in a GCM land surface scheme. *Journal of Hydrology*, **212-213**, 79-94.

Cox, P.M., D. Pearson, B.B. Booth, P. Friedlingstein, C. Huntingford, C.D. Jones, and C.M. Luke, 2013: Sensitivity of tropical carbon to climate change constrained by carbon dioxide variability. *Nature*, **494(7437)**, 341-344.

Crimmins, S.M., S.Z. Dobrowski, J.A. Greenberg, J.T. Abatzoglou, and A.R. Mynsberge, 2011: Changes in climatic water balance drive downhill shifts in plant species' optimum elevations. *Science*, **331(6015)**, 324-327.

Crimmins, T.M., M.A. Crimmins, and C.D. Bertelsen, 2009: Flowering range changes across an elevation gradient in response to warming summer temperatures. *Global Change Biology*, **15(5)**, 1141-1152.

Crossman, J., M.N. Futter, S.K. Oni, P.G. Whitehead, L. Jin, D. Butterfield, H.M. Baulch, and P.J. Dillon, 2013: Impacts of climate change on hydrology and water quality: future proofing management strategies in the Lake Simcoe watershed, Canada. *Journal of Great Lakes Research*, **39(1)**, 19-32.

Crous, C.J., S.M. Jacobs, and K.J. Esler, 2012: Drought-tolerance of an invasive alien tree, *Acacia mearnsii* and two native competitors in fynbos riparian ecotones. *Biological Invasions*, **14(3)**, 619-631.

Cui, X.F. and H.F. Graf, 2009: Recent land cover changes on the Tibetan Plateau: a review. *Climatic Change*, **94(1-2)**, 47-61.

Curran, L.M., S.N. Trigg, A.K. McDonald, D. Astiani, Y.M. Hardiono, P. Siregar, I. Caniago, and E. Kasischke, 2004: Lowland forest loss in protected areas of Indonesian Borneo. *Science*, **303(5660)**, 1000-1003.

da Costa, A.C.L., D. Galbraith, S. Almeida, B.T.T. Portela, M. Da Costa, J. De Athaydes Silva Junior, A.P. Braga, P.H.L. De Gonçalves, A.A. De Oliveira, R. Fisher, O.L. Phillips, D.B. Metcalfe, P. Levy, and P. Meir, 2010: Effect of 7 yr of experimental drought on vegetation dynamics and biomass storage of an eastern Amazonian rainforest. *New Phytologist*, **187(3)**, 579-591.

Dahm, C.N., M.A. Baker, D.I. Moore, and J.R. Thibault, 2003: Coupled biogeochemical and hydrological responses of streams and rivers to drought. *Freshwater Biology*, **48(7)**, 1219-1231.

Dai, F., Z. Su, S. Liu, and G. Liu, 2011: Temporal variation of soil organic matter content and potential determinants in Tibet, China. *Catena*, **85(3)**, 288-294.

Dale, V.H., M.L. Tharp, K.O. Lannom, and D.G. Hodges, 2010: Modeling transient response of forests to climate change. *Science of the Total Environment*, **408(8)**, 1888-1901.

Danby, R.K., and D.S. Hik, 2007: Variability, contingency and rapid change in recent subarctic alpine tree line dynamics. *Journal of Ecology*, **95(2)**, 352-363.

Daniau, A.L., S.P. Harrison, and P.J. Bartlein, 2010: Fire regimes during the Last Glacial. *Quaternary Science Reviews*, **29(21-22)**, 2918-2930.

Daniau, A.L., P.J. Bartlein, S.P. Harrison, I.C. Prentice, S. Brewer, P. Friedlingstein, T.I. Harrison-Prentice, J. Inoue, K. Izumi, J.R. Marlon, S. Mooney, M.J. Power, J. Stevenson, W. Tinner, M. Andric, J. Atanassova, H. Behling, M. Black, O. Blarquez, K.J. Brown, C. Carcaillet, E.A. Colhoun, D. Colombaroli, B.A.S. Davis, D. D'Costa, J. Dodson, L. Dupont, Z. Eshetu, D.G. Gavin, A. Genries, S. Haberle, D.J. Hallett, G. Hope, S.P. Horn, T.G. Kassa, F. Katamura, L.M. Kennedy, P. Kershaw, S. Krivonogov, C. Long, D. Magri, E. Marinova, G.M. McKenzie, P.I. Moreno, P. Moss, F.H. Neumann, E. Norstrom, C. Paitre, D. Rius, N. Roberts, G.S. Robinson, N. Sasaki, L. Scott, H. Takahara, V. Terwilliger, F. Thevenon, R. Turner, V.G. Valsecchi, B. Vanniere, M. Walsh, N. Williams, and Y. Zhang, 2012: Predictability of biomass burning in response to climate changes. *Global Biogeochemical Cycles*, **26(4)**, GB4007, doi:10.1029/2011GB004249.

Daufresne, M. and P. Boet, 2007: Climate change impacts on structure and diversity of fish communities in rivers. *Global Change Biology*, **13(12)**, 2467-2478.

Davidson, A.M., M. Jennions, and A.B. Nicotra, 2011: Do invasive species show higher phenotypic plasticity than native species and, if so, is it adaptive? A meta-analysis. *Ecology Letters*, **14(4)**, 419-431.

Davidson, E.A. and I.A. Janssens, 2006: Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, **440**, 165-173.

Davidson, E.A., A.C. de Araujo, P. Artaxo, J.K. Balch, I.F. Brown, M.M.C. Bustamante, M.T. Coe, R.S. DeFries, M. Keller, M. Longo, J.W. Munger, W. Schroeder, B.S. Soares, C.M. Souza, and S.C. Wofsy, 2012: The Amazon basin in transition. *Nature*, **481(7381)**, 321-328.

Davies, P.M., 2010: Climate change implications for river restoration in global biodiversity hotspots. *Restoration Ecology*, **18(3)**, 261-268.

Davin, E.L. and N. de Noblet-Ducoudre, 2010: Climatic impact of global-scale deforestation: radiative versus nonradiative processes. *Journal of Climate*, **23(1)**, 97-112.

Davin, E.L., N. de Noblet-Ducoudre, and P. Friedlingstein, 2007: Impact of land cover change on surface climate: relevance of the radiative forcing concept. *Geophysical Research Letters*, **34(13)**, L13702, doi:10.1029/2007GL029678.

Davis, C.C., C.G. Willis, R.B. Primack, and A.J. Miller-Rushing, 2010: The importance of phylogeny to the study of phenological response to global climate change. *Philosophical Transactions of the Royal Society B*, **365(1555)**, 3201-3213.

Davis, J.L., S. Lake, and R. Thompson, 2010: Freshwater biodiversity and climate change. In: *Managing Climate Change: Papers from the Greenhouse 2009 Conference* [Jubb, I., P. Holper, and W. Cai (eds.)]. Commonwealth Scientific and Industrial Research Organisation (CSIRO) Publishing, Collingwood, Australia, pp. 73-84.

Dawes, M.A., S. Hättenschwiler, P. Bebi, F. Hagedorn, I.T. Handa, C. Körner, and C. Rixen, 2011: Species-specific tree growth responses to 9 years of CO_2 enrichment at the alpine treeline. *Journal of Ecology*, **99(2)**, 383-394.

Dawson, T.P., S.T. Jackson, J.I. House, I.C. Prentice, and G.M. Mace, 2011: Beyond predictions: biodiversity conservation in a changing climate. *Science*, **332(6025)**, 53-58.

de Jong, R., S. de Bruin, A. de Wit, M.E. Schaepman, and D.L. Dent, 2011: Analysis of monotonic greening and browning trends from global NDVI time-series. *Remote Sensing of Environment*, **115(2)**, 692-702.

De Kauwe, M.G., B.E. Medlyn, S. Zaehle, A.P. Walker, M.C. Dietze, T. Hickler, A.K. Jain, Y. Luo, W.J. Parton, C. Prentice, B. Smith, P.E. Thornton, S. Wang, Y.-P. Wang, D. Wårlind, E.S. Weng, K.Y. Crous, D.S. Ellsworth, P.J. Hanson, H. Seok-Kim, J.M. Warren, R. Oren, and R.J. Norby, 2013: Forest water use and water use efficiency at elevated CO_2: a model-data intercomparison at two contrasting temperate forest FACE sites. *Global Change Biology*, **19(6)**, 1759-1779.

De Michele, C., F. Accatino, R. Vezzoli, and R.J. Scholes, 2011: Savanna domain in the herbivores-fire parameter space exploiting a tree–grass–soil water dynamic model. *Journal of Theoretical Biology*, **289**, 74-82.

de Noblet-Ducoudre, N., J.P. Boisier, A. Pitman, G.B. Bonan, V. Brovkin, F. Cruz, C. Delire, V. Gayler, B.J.J.M. van den Hurk, P.J. Lawrence, M.K. van der Molen, C. Muller, C.H. Reick, B.J. Strengers, and A. Voldoire, 2012: Determining robust impacts of land-use-induced land cover changes on surface climate over North America and Eurasia: results from the first set of LUCID experiments. *Journal of Climate*, **25(9)**, 3261-3281.

de Torres Curth, M.I., L. Ghermandi, and C. Biscayart, 2012: Are *Fabiana imbricata* shrublands advancing over northwestern Patagonian grasslands? A population dynamics study involving fire and precipitation. *Journal of Arid Environments*, **83**, 78-85.

de Vries, W. and M. Posch, 2011: Modelling the impact of nitrogen deposition, climate change and nutrient limitations on tree carbon sequestration in Europe for the period 1900-2050. *Environmental Pollution*, **159(10)**, 2289-2299.

DeFries, R.S., T. Rudel, M. Uriarte, and M. Hansen, 2010: Deforestation driven by urban population growth and agricultural trade in the twenty-first century. *Nature Geoscience*, **3(3)**, 178-181.

Delire, C., N. de Noblet-Ducoudre, A. Sima, and I. Gouirand, 2011: Vegetation dynamics enhancing long-term climate variability confirmed by two models. *Journal of Climate*, **24(9)**, 2238-2257.

Denman, K.L., G. Brasseur, A. Chidthaisong, P. Ciais, P.M. Cox, R.E. Dickinson, D. Hauglustaine, C. Heinze, E. Holland, D. Jacob, U. Lohmann, S. Ramachandran, P.L. da Silva Dias, S.C. Wofsy, and X. Zhang, 2007: Couplings between changes in the climate system and biogeochemistry. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA., pp. 499-587.

Dentener, F., T. Keating, and H. Akimoto (eds.), 2010: *Hemispheric Transport of Air Pollution 2010: Part A – Ozone and Particulate Matter.* United Nations Economic Commission for Europe (UNECE) Air Pollution Series Studies No. 17, United Nations, New York, NY, USA and Geneva, Switzerland, 304 pp.

DeRose, R.J. and J.N. Long, 2012: Drought-driven disturbance history characterizes a southern Rocky Mountain subalpine forest. *Canadian Journal of Forest Research / Revue Canadienne De Recherche Forestiere*, **42(9)**, 1649-1660.

Deutsch, C.A., J.J. Tewksbury, R.B. Huey, K.S. Sheldon, C.K. Ghalambor, D.C. Haak, and P.R. Martin, 2008: Impacts of climate warming on terrestrial ectotherms across latitude. *Proceedings of the National Academy of Sciences of the United States of America*, **105(18)**, 6668-6672.

Devi, N., F. Hagedorn, P. Moiseev, H. Bugmann, S. Shiyatov, V. Mazepa, and A. Rigling, 2008: Expanding forests and changing growth forms of Siberian larch at the Polar Urals treeline during the 20th century. *Global Change Biology*, **14(7)**, 1581-1591.

Devictor, V., C. van Swaay, T. Brereton, L. Brotons, D. Chamberlain, J. Heliola, S. Herrando, R. Julliard, M. Kuussaari, A. Lindstrom, J. Reif, D.B. Roy, O. Schweiger, J. Settele, C. Stefanescu, A. Van Strien, C. Van Turnhout, Z. Vermouzek, M. Wallis DeVries, I. Wynhoff, and F. Jiguet, 2012: Differences in the climatic debts of birds and butterflies at a continental scale. *Nature Climate Change*, **2(2)**, 121-124.

Dial, R.J., E.E. Berg, K. Timm, A. McMahon, and J. Geck, 2007: Changes in the alpine forest-tundra ecotone commensurate with recent warming in southcentral Alaska: evidence from orthophotos and field plots. *Journal of Geophysical Research: Biogeosciences*, **112(G4)**, G04015, doi:10.1029/2007JG000453.

Dieleman, W.I.J., S. Vicca, F.A. Dijkstra, F. Hagedorn, M.J. Hovenden, K.S. Larsen, J.A. Morgan, A. Volder, C. Beier, J.S. Dukes, J. King, S. Leuzinger, S. Linder, Y. Luo, R. Oren, P. De Angelis, D. Tingey, M.R. Hoosbeek, and I.A. Janssens, 2012: Simple additive effects are rare: a quantitative review of plant biomass and soil process responses to combined manipulations of CO_2 and temperature. *Global Change Biology*, **18(9)**, 2681-2693.

Diez, J.M., C.M. D'Antonio, J.S. Dukes, E.D. Grosholz, J.D. Olden, C.J.B. Sorte, D.M. Blumenthal, B.A. Bradley, R. Early, I. Ibanez, S.J. Jones, J.J. Lawler, and L.P. Miller, 2012: Will extreme climatic events facilitate biological invasions? *Frontiers in Ecology and the Environment*, **10(5)**, 249-257.

Diffenbaugh, N.S. and F. Giorgi, 2012: Climate change hotspots in the CMIP5 global climate model ensemble. *Climatic Change*, **114(3-4)**, 813-822.

Diffenbaugh, N.S., J.S. Pal, R.J. Trapp, and F. Giorgi, 2005: Fine-scale processes regulate the response of extreme events to global climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **102(44)**, 15774-15778.

Dise, N.B., 2009: Peatland response to global change. *Science*, **326(5954)**, 810-811.

Doak, D.F. and W.F. Morris, 2010: Demographic compensation and tipping points in climate-induced range shifts. *Nature*, **467(7318)**, 959-962.

Dobrowski, S.Z., J. Abatzoglou, A.K. Swanson, J.A. Greenberg, A.R. Mynsberge, Z.A. Holden, and M.K. Schwartz, 2013: The climate velocity of the contiguous United States during the 20th century. *Global Change Biology*, **19(1)**, 241-251.

Dohrenbusch, A. and A. Bolte, 2007: Forest plantations. In: *Wood Production, Wood Technology and Biotechnological Impacts* [Kües, U. (ed.)]. Universitätsverlag Göttingen, Göttingen, Germany, pp. 73-83.

Donnelly, A., A. Caffarra, C.T. Kelleher, B.F. O'Neill, E. Diskin, A. Pletsers, H. Proctor, R. Stirnemann, J. O'Halloran, J. Penuelas, T.R. Hodkinson, and T.H. Sparks, 2012: Surviving in a warmer world: environmental and genetic responses. *Climate Research*, **53(3)**, 245-262.

Donohue, R.J., T.R. McVicar, M.L. Roderick,, and G.D. Farquhar, 2013: Impact of CO_2 fertilization on maximum foliage coveracross the globe's warm, arid environments. *Geophysical Research Letters*, **40**, 3031-3035.

Doughty, C.E. and M.L. Goulden, 2008: Are tropical forests near a high temperature threshold? *Journal of Geophysical Research: Biogeosciences*, **113(G1)**, G00B07, doi:10.1029/2007JG000632.

Doughty, C.E., C.B. Field, and A.M.S. McMillan, 2011: Can crop albedo be increased through modification of leaf trichomes, and could this cool the regional climate? *Climatic Change*, **104(2)**, 379-387.

Douville, H., A. Ribes, B. Decharme, R. Alkama, and J. Sheffield, 2013: Anthropogenic influence on multidecadal changes in reconstructed global evapotranspiration. *Nature Climate Change*, **3(1)**, 59-62.

Doxford, S.W. and R.P. Freckleton, 2012: Changes in the large-scale distribution of plants: extinction, colonisation and the effects of climate. *Journal of Ecology*, **100(2)**, 519-529.

Drewitt, A.L. and R.H.W. Langston, 2006: Assessing the impacts of wind farms on birds. *Ibis*, **148**, 29-42.

Dudgeon, D., A.H. Arthington, M.O. Gessner, Z.I. Kawabata, D.J. Knowler, C. Leveque, R.J. Naiman, A.H. Prieur-Richard, D. Soto, M.L.J. Stiassny, and C.A. Sullivan, 2006: Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological Reviews*, **81(2)**, 163-182.

Dukes, J.S., J. Pontius, D. Orwig, J.R. Garnas, V.L. Rodgers, N. Brazee, B. Cooke, K.A. Theoharides, E.E. Stange, R. Harrington, J. Ehrenfeld, J. Gurevitch, M. Lerdau, K. Stinson, R. Wick, and M. Ayres, 2009: Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: what can we predict? *Canadian Journal of Forest Research / Revue Canadienne De Recherche Forestiere*, **39(2)**, 231-248.

Dulamsuren, C., M. Hauck, S. Nyambayar, M. Bader, D. Osokhjargal, S. Oyungerel, and C. Leuschner, 2009: Performance of Siberian elm (*Ulmus pumila*) on steppe slopes of the northern Mongolian mountain taiga: drought stress and herbivory in mature trees. *Environmental and Experimental Botany*, **66(1)**, 18-24.

Dullinger, S., A. Gattringer, W. Thuiller, D. Moser, N.E. Zimmermann, A. Guisan, W. Willner, C. Plutzar, M. Leitner, T. Mang, M. Caccianiga, T. Dirnbock, S. Ertl, A. ischer, J. Lenoir, J.C. Svenning, A. Psomas, D.R. Schmatz, U. Silc, P. Vittoz, and K. Hulber, 2012: Extinction debt of high-mountain plants under twenty-first-century climate change. *Nature Climate Change*, **2(8)**, 619-622.

Dunlop, M., D.W. Hilbert, S. Ferrier, A. House, A. Liedloff, S.M. Prober, A. Smyth, T.G. Martin, T. Harwood, K.J. Williams, C. Fletcher, and H. Murphy, 2012: *The Implications of Climate Change for Biodiversity Conservation and the National Reserve System: Final Synthesis.* Canberra, ACT, Australia, 80 pp.

Dunn, R.R., N.C. Harris, R.K. Colwell, L.P. Koh, and N.S. Sodhi, 2009: The sixth mass coextinction: are most endangered species parasites and mutualists? *Proceedings of the Royal Society B*, **276(1670)**, 3037-3045.

Durance, I. and S.J. Ormerod, 2007: Climate change effects on upland stream macroinvertebrates over a 25-year period. *Global Change Biology*, **13(5)**, 942-957.

Eamus, D. and A.R. Palmer, 2007: Is climate change a possible explanation for woody thickening in arid and semi-arid regions? *International Journal of Ecology*, **2007**, 37364, doi:10.1155/2007/37364.

Eastaugh, C.S., E. Potzelsberger, and H. Hasenauer, 2011: Assessing the impacts of climate change and nitrogen deposition on Norway spruce (*Picea abies* L. Karst) growth in Austria with BIOME-BGC. *Tree Physiology*, **31(3)**, 262-274.

Edburg, S.L., J.A. Hicke, P.D. Brooks, E.G. Pendall, B.E. Ewers, U. Norton, D. Gochis, E.D. Gutmann, and A.J.H. Meddens, 2012: Cascading impacts of bark beetle-caused tree mortality on coupled biogeophysical and biogeochemical processes. *Frontiers in Ecology and the Environment*, **10(8)**, 416-424.

Eggermont, H., D. Verschuren, L. Audenaert, L. Lens, J. Russell, G. Klaassen, and O. Heiri, 2010: Limnological and ecological sensitivity of Rwenzori mountain lakes to climate warming. *Hydrobiologia*, **648(1)**, 123-142.

Eisenhauer, N., S. Cesarz, R. Koller, K. Worm, and P.B. Reich, 2012: Global change belowground: impacts of elevated CO_2, nitrogen, and summer drought on soil food webs and biodiversity. *Global Change Biology*, **18(2)**, 435-447.

Eliasch, J., 2008: *Climate Change: Financing Global Forests – The Eliasch Review*. Earthscan, Abingdon, UK and New York, NY, USA , 288 pp.

Elith, J. and J.R. Leathwick, 2009: Species distribution models: ecological explanation and prediction across space and time. *Annual Review of Ecology Evolution and Systematics*, **40**, 677-697.

Ellery, W.N., R.J. Scholes, and M.T. Mentis, 1991: An initial approach to predicting the sensitivity of the South African grassland biome to climate change. *South African Journal of Science*, **87**, 499-503.

Elmendorf, S.C., G.H.R. Henry, R.D. Hollister, R.G. Bjork, N. Boulanger-Lapointe, E.J. Cooper, J.H.C. Cornelissen, T.A. Day, E. Dorrepaal, T.G. Elumeeva, M. Gill, W.A. Gould, J. Harte, D.S. Hik, A. Hofgaard, D.R. Johnson, J.F. Johnstone, I.S. Jonsdottir, J.C. Jorgenson, K. Klanderud, J.A. Klein, S. Koh, G. Kudo, M. Lara, E. Levesque, B. Magnusson, J.L. May, J.A. Mercado-Diaz, A. Michelsen, U. Molau, I.H. Myers-Smith, S.F. Oberbauer, V.G. Onipchenko, C. Rixen, N. Martin Schmidt, G.R. Shaver, M.J. Spasojevic, o.E. orhallsdottir, A. Tolvanen, T. Troxler, C.E. Tweedie, S. Villareal, C.-H. Wahren, X. Walker, P.J. Webber, J.M. Welker, and S. Wipf, 2012: Plot-scale evidence of tundra vegetation change and links to recent summer warming. *Nature Climate Change*, **2(6)**, 453-457.

Elser, J.J., M.E.S. Bracken, E.E. Cleland, D.S. Gruner, W.S. Harpole, H. Hillebrand, J.T. Ngai, E.W. Seabloom, J.B. Shurin, and J.E. Smith, 2007: Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. *Ecology Letters*, **10**, 1135-1142.

Elser, J.J., T. Andersen, J.S. Baron, A.K. Bergström, M. Jansson, M. Kyle, K.R. Nydick, L. Steger, and D.O. Hessen, 2009: Shifts in lake N:P stoichiometry and nutrient limitation driven by atmospheric nitrogen deposition. *Science*, **326(5954)**, 835-837.

Emmett, B.A., C. Beier, M. Estiarte, A. Tietema, H.L. Kristensen, D. Williams, J. Penuelas, I. Schmidt, and A. Sowerby, 2004: The response of soil processes to climate change: results from manipulation studies of shrublands across an environmental gradient. *Ecosystems*, **7(6)**, 625-637.

Engler, R., C.F. Randin, W. Thuiller, S. Dullinger, N.E. Simmermann, M.B. Araujo, P.B. Pearman, G. Le Lay, C. Peidallu, C.H. Albert, P. Choler, G. Coldea, S. De Lamo, T. Dirnbock, J.C. Gegout, D. Gomez-Garcia, J.A. Grytnes, E. Heegaard, F. Hoistad, D. Nogues-Bravo, S. Normand, M. Puscas, M.T. Sebastia, A. Stanisci, J.P. Theurillat, M.R. Trivedi, P. Vittoz, and A. Guisan, 2011: 21st century climate change threatens mountain flora unequally across Europe. *Global Change Biology*, **17(7)**, 2330-2341.

Enquist, B.J. and C.A.F. Enquist, 2011: Long-term change within a Neotropical forest: assessing differential functional and floristic responses to disturbance and drought. *Global Change Biology*, **17(3)**, 1408-1424.

Epstein, H., J. Kaplan, H. Lischke, and Q. Yu, 2007: Simulating future changes in arctic tundra and sub-arctic vegetation. *Computing in Science and Engineering*, **9**, 12-23.

Epstein, H.E., D. A. Walker, M. K. Raynolds, G. J. Jia, and A. M. Kelley, 2008: Phytomass patterns across a temperature gradient of the North American arctic tundra. *Journal of Geophysical Research: Biogeosciences*, **113(G3)**, G03S02, doi:10.1029/2007JG000555.

Erlandsson, M., I. Buffam, J. Folster, H. Laudon, J. Temnerud, G.A. Weyhenmeyer, and K. Bishop, 2008: Thirty-five years of synchrony in the organic matter concentrations of Swedish rivers explained by variation in flow and sulphate. *Global Change Biology*, **14(5)**, 1191-1198.

Erskine, P.D., D. Lamb, and M. Bristow, 2006: Tree species diversity and ecosystem function: can tropical multi-species plantations generate greater productivity? *Forest Ecology and Management*, **233(2-3)**, 205-210.

Essl, F., S. Dullinger, D. Moser, W. Rabitsch, and I. Kleinbauer, 2012: Vulnerability of mires under climate change: implications for nature conservation and climate change adaptation. *Biodiversity and Conservation*, **21(3)**, 655-669.

EU Council, 1992: *Council Directive 92/43/EEC of 21 May 1992 on the Conservation of Natural Habitats and of Wild Fauna and Flora.* The Council of the European Communities, Brussels, Belgium, 66 pp.

Euskirchen, E.S., A.D. McGuire, F.S. Chapin III, S. Yi, and C.C. Thompson, 2009: Changes in vegetation in northern Alaska under scenarios of climate change, 2003-2100: implications for climate feedbacks. *Ecological Applications*, **19(4)**, 1022-1043.

Evans, C.D., D.T. Monteith, and D.M. Cooper, 2005: Long-term increases in surface water dissolved organic carbon: observations, possible causes and environmental impacts. *Environmental Pollution*, **137(1)**, 55- 71.

Eycott, A.E., G.B. Stewart, L.M. Buyung-Ali, D.E. Bowler, K. Watts, and A.S. Pullin, 2012: A meta-analysis on the impact of different matrix structures on species movement rates. *Landscape Ecology*, **27(9)**, 1263-1278.

Fahey, T.J., 1998: Recent changes in an upland forest in South-Central New York. *Journal of the Torrey Botanical Society*, **125(1)**, 51-59.

Fall, S., D. Niyogi, A. Gluhovsky, R.A. Pielke, E. Kalnay, and G. Rochon, 2010: Impacts of land use land cover on temperature trends over the continental United States: assessment using the North American Regional Reanalysis. *International Journal of Climatology*, **30(13)**, 1980-1993.

Falloon, P.D., R. Dankers, R.A. Betts, C.D. Jones, B.B.B. Booth, and F.H. Lambert, 2012: Role of vegetation change in future climate under the A1B scenario and a climate stabilisation scenario, using the HadCM3C earth systems model. *Biogeosciences*, **9(11)**, 4739-4756.

FAO, 2005: *Global Forest Resources Assessment 2005.* FAO Forestry Paper No. 147, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 350 pp.

FAO, 2010: *Global Forest Resources Assessment 2010.* FAO Forestry Paper No. 163, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 340 pp.

Farquhar, G.D., S. von Caemmerer, and J.A. Berry, 1980: A biochemical model of photosynthetic CO_2 assimilation in leaves of C3 species. *Planta*, **149**, 78-90.

Fauset, S., T.R. Baker, S.L. Lewis, T.R. Feldpausch, K. Affum-Baffoe, E.G. Foli, K.C. Hamer, and M.D. Swaine, 2012: Drought-induced shifts in the floristic and functional composition of tropical forests in Ghana. *Ecology Letters*, **15(10)**, 1120-1129.

Fay, P.A., J.D. Carlisle, A.K. Knapp, J.M. Blair, and S.L. Collins, 2003: Productivity responses to altered rainfall patterns in a C_4-dominated grassland. *Oecologia*, **137(2)**, 245-251.

Feeley, K.J. and E.M. Rehm, 2012: Amazon's vulnerability to climate change heightened by deforestation and man-made dispersal barriers. *Global Change Biology*, **18(12)**, 3606-3614.

Fellows, A.W. and M.L. Goulden, 2012: Rapid vegetation redistribution in Southern California during the early 2000s drought. *Journal of Geophysical Research: Biogeosciences*, **117(G3)**, G03025, doi:10.1029/2012JG002044.

Fensham, R.J., R.J. Fairfax, and D.P. Ward, 2009: Drought-induced tree death in savanna. *Global Change Biology*, **15**, 380-387.

Fensham, R.J., R.J. Fairfax, and J.M. Dwyer, 2012: Potential aboveground biomass in drought-prone forest used for rangeland pastoralism. *Ecological Applications*, **22(3)**, 894-908.

Fensholt, R., T. Langanke, K. Rasmussen, A. Reenberg, S.D. Prince, C. Tucker, B. Scholes, Q.B. Le, A. Bondeau, R. Eastman, H. Epstein, A.E. Gaughan, U. Hellden, C. Mbow, L. Olsson, J. Paruelo, C. Schweitzer, J. Seaquist, and K. Wessels, 2012: Greenness in semi-arid areas across the globe 1981-2007 – an Earth Observing Satellite based analysis of trends and drivers. *Remote Sensing of Environment*, **121**, 144-158.

Ferriere, R. and S. Legendre, 2013: Eco-evolutionary feedbacks, adaptive dynamics and evolutionary rescue theory. *Philosophical Transactions of the Royal Society B*, **368(1610)**, 20120081, doi:10.1098/rstb.2012.0404.

Ficke, A.D., C.A. Myrick, and L.J. Hansen, 2007: Potential impacts of global climate change on freshwater fisheries. *Reviews in Fish Biology and Fisheries*, **17(4)**, 581-613.

Field, C.B., D.B. Lobell, H.A. Peters, and N.R. Chiariello, 2007: Feedbacks of terrestrial ecosystems to climate change. *Annual Review of Environment and Resources*, **32**, 1-29, doi:10.1146/annurev.energy.32.053006.141119.

Findell, K.L., E. Shevliakova, P.C.D. Milly, and R.J. Stouffer, 2007: Modeled impact of anthropogenic land cover change on climate. *Journal of Climate*, **20(14)**, 3621-3634.

Finn, D.S., K. Khamis, and A.M. Milner, 2013: Loss of small glaciers will diminish beta diversity in Pyrenean streams at two levels of biological organization. *Global Ecology and Biogeography*, **22(1)**, 40-51.

Finzi, A.C., R.J. Norby, C. Calfapietra, A. Gallet-Budynek, B. Gielen, W.E. Holmes, M.R. Hoosbeek, C.M. Iversen, R.B. Jackson, M.E. Kubiske, J. Ledford, M. Liberloo, R. Oren, A. Polle, S. Pritchard, D.R. Zak, W.H. Schlesinger, and R. Ceulemans, 2007: Increases in nitrogen uptake rather than nitrogen-use efficiency support higher rates of temperate forest productivity under elevated CO_2. *Proceedings of the National Academy of Sciences of the United States of America*, **104(35)**, 14014-14019.

Fiorese, G. and G. Guariso, 2013: Modeling the role of forests in a regional carbon mitigation plan. *Renewable Energy*, **52**, 175-182.

Fischer, J. and D.B. Lindenmayer, 2007: Landscape modification and habitat fragmentation: a synthesis. *Global Ecology and Biogeography*, **16(3)**, 265-280.

Fischlin, A., G.F. Midgley, J.T. Price, R. Leemans, B. Gopal, C. Turley, M.D.A. Rounsevell, O.P. Dube, J. Tarazona, and A.A. Velichko, 2007: Ecosystems, their properties, goods, and services. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 211-272.

Fisher, J.B., G. Hurtt, R.Q. Thomas, and J.Q. Chambers, 2008: Clustered disturbances lead to bias in large-scale estimates based on forest sample plots. *Ecology Letters*, **11(6)**, 554-563.

Fisher, R., N. McDowell, D. Purves, P. Moorcroft, S. Sitch, P. Cox, C. Huntingford, P. Meir, and F. Ian Woodward, 2010: Assessing uncertainties in a second-generation dynamic vegetation model caused by ecological scale limitations. *New Phytologist*, **187(3)**, 666-681.

FLUXNET, 2012: *Historical Site Status*. fluxnet.ornl.gov/site_status.

Foden, W.B., S.H.M. Butchart, S.N. Stuart, J.C. Vie, H.R. Akcakaya, A. Angulo, L.M. DeVantier, A. Gutsche, E. Turak, L. Cao, S.D. Donner, V. Katariya, R. Bernard, R.A. Holland, A.F. Hughes, S.E. O'Hanlon, S.T. Garnett, C.H. Sekercioglu, and G.M. Mace, 2013: Identifying the world's most climate change vulnerable species: a systematic trait-based assessment of all birds, amphibians and corals. *PLoS One*, **8(6)**, e65427, doi:10.1371/journal.pone.0065427.

Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, and C.S. Holling, 2004: Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Review of Ecology Evolution and Systematics*, **35**, 557-581.

Forbes, B.C., M.M. Fauria, and P. Zetterberg, 2010: Russian Arctic warming and 'greening' are closely tracked by tundra shrub willows. *Global Change Biology*, **16(5)**, 1542-1554.

Fordham, D.A., H.R. Akcakaya, M.B. Araujo, J. Elith, D.A. Keith, R. Pearson, T.D. Auld, C. Mellin, J.W. Morgan, T.J. Regan, M. Tozer, M.J. Watts, M. White, B.A. Wintle, C. Yates, and B.W. Brook, 2012: Plant extinction risk under climate change: are forecast range shifts alone a good indicator of species vulnerability to global warming? *Global Change Biology*, **18(4)**, 1357-1371.

Fowler, D., M. Coyle, U. Skiba, M.A. Sutton, J.N. Cape, S. Reis, L.J. Sheppard, A. Jenkins, B. Grizzetti, J.N. Galloway, P. Vitousek, A. Leach, A.F. Bouwman, K. Butterbach-Bahl, F. Dentener, D. Stevenson, M. Amann, and M. Voss, 2013: The global nitrogen cycle in the twenty-first century. *Philosophical Transactions of the Royal Society B*, **368(1621)**, 20130164, doi:10.1098/rstb.2013.0164.

Franklin, J., F.W. Davis, M. Ikegami, A.D. Syphard, L.E. Flint, A.L. Flint, and L. Hannah, 2013: Modeling plant species distributions under future climates: how fine scale do climate projections need to be? *Global Change Biology*, **19(2)**, 473-483.

Franks, S.J. and A.A. Hoffmann, 2012: Genetics of climate change adaptation. *Annual Review of Genetics*, **46**, 185-208.

Franks, S.J. and A.E. Weis, 2008: A change in climate causes rapid evolution of multiple life-history traits and their interactions in an annual plant. *Journal of Evolutionary Biology*, **21(5)**, 1321-1334.

Frelich, L.E., R.O. Peterson, M. Dovciak, P.B. Reich, J.A. Vucetich, and N. Eisenhauer, 2012: Trophic cascades, invasive species and body-size hierarchies interactively modulate climate change responses of ecotonal temperate-boreal forest. *Philosophical Transactions of the Royal Society B*, **367(1605)**, 2955-2961.

Friend, A., W. Lucht, T.T. Rademacher, R.M. Keribin, R. Betts, P. Cadule, P. Ciais, D.B. Clark, R. Dankers, P. Falloon, A. Ito, R. Kahana, A. Kleidon, M.R. Lomas, K. Nishina, S. Ostberg, R. Pavlick, P. Peylin, S. Schaphoff, N. Vuichard, L. Warszawski, A. Wiltshire, and F.I. Woodward, 2013: Carbon residence time dominates uncertainty in terrestrial vegetation responses to future climate and atmospheric CO_2. *Proceedings of the National Academy of Science of the United States of America* (in press), doi:10.1073/pnas.1222477110.

Frolking, S., J. Talbot, M.C. Jones, C.C. Treat, J.B. Kauffman, E.S. Tuittila, and N. Roulet, 2011: Peatlands in the Earth's 21st century climate system. *Environmental Reviews*, **19**, 371-396.

Fujino, J., R. Nair, M. Kainuma, T. Masui, and Y. Matsuoka, 2006: Multi-gas mitigation analysis on stabilization scenerios using AIM global model. *The Energy Journal*, **SI 3**, 343-354.

Gagen, M., W. Finsinger, F. Wagner-Cremer, D. McCarroll, N.J. Loader, I. Robertson, R. Jalkanen, G. Young, and A. Kirchhefer, 2011: Evidence of changing intrinsic water-use efficiency under rising atmospheric CO_2 concentrations in Boreal Fennoscandia from subfossil leaves and tree ring ^{13}C ratios. *Global Change Biology*, **17(2)**, 1064-1072.

Galiano, L., J. Martínez-Vilalta, and F. Lloret, 2010: Drought-induced multifactor decline of Scots pine in the Pyrenees and potential vegetation change by the expansion of co-occurring oak species. *Ecosystems*, **13(7)**, 978-991.

Gallant, D., B.G. Slough, D.G. Reid, and D. Berteaux, 2012: Arctic fox versus red fox in the warming Arctic: four decades of den surveys in north Yukon. *Polar Biology*, **35(9)**, 1421-1431.

Galloway, J.N., A.R. Townsend, J.W. Erisman, M. Bekunda, Z.C. Cai, J.R. Freney, L.A. Martinelli, S.P. Seitzinger, and M.A. Sutton, 2008: Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. *Science*, **320(5878)**, 889-892.

Ganey, J.L. and S.C. Vojta, 2011: Tree mortality in drought-stressed mixed-conifer and ponderosa pine forests, Arizona, USA. *Forest Ecology and Management*, **261(1)**, 162-168.

Gao, J. and Y. Liu, 2011: Climate warming and land use change in Heilongjiang Province, Northeast China. *Applied Geography*, **31(2)**, 476-482.

Gao, X.J. and F. Giorgi, 2008: Increased aridity in the Mediterranean region under greenhouse gas forcing estimated from high resolution simulations with a regional climate model. *Global and Planetary Change*, **62(3-4)**, 195-209.

Garreta, V., P.A. Miller, J. Guiot, C. Hely, S. Brewer, M.T. Sykes, and T. Litt, 2010: A method for climate and vegetation reconstruction through the inversion of a dynamic vegetation model. *Climate Dynamics*, **35(2-3)**, 371-389.

Garrity, S.R., C.D. Allen, S.P. Brumby, C. Gangodagamage, N.G. McDowell, and D.M. Cai, 2013: Quantifying tree mortality in a mixed species woodland using multitemporal high spatial resolution satellite imagery. *Remote Sensing of Environment*, **129**, 54-65.

Gaudnik, C., E. Corcket, B. Clement, C.E.L. Delmas, S. Gombert-Courvoisier, S. Muller, C.J. Stevens, and D. Alard, 2011: Detecting the footprint of changing atmospheric nitrogen deposition loads on acid grasslands in the context of climate change. *Global Change Biology*, **17(11)**, 3351-3365.

Gauthier, G., J. Bety, M.-C. Cadieux, P. Legagneux, M. Doiron, C. Chevallier, S. Lai, A. Tarroux, and D. Berteaux, 2013: Long-term monitoring at multiple trophic levels suggests heterogeneity in responses to climate change in the Canadian Arctic tundra. *Philosophical Transactions of the Royal Society B*, **368(1624)**, doi: 10.1098/rstb.2012.0482.

Gedalof, Z. and A.A. Berg, 2010: Tree ring evidence for limited direct CO_2 fertilization of forests over the 20th century. *Global Biogeochemical Cycles*, **24(3)**, GB3027, doi:10.1029/2009GB003699.

Gerten, D., S. Rost, W. von Bloh, and W. Lucht, 2008: Causes of change in 20th century global river discharge. *Geophysical Research Letters*, **35(20)**, L20405, doi:10.1029/2008GL035258.

Ghermandi, L., M.I.D. Curth, J. Franzese, and S. Gonzalez, 2010: Non-linear ecological processes, fires, environmental heterogeneity and shrub invasion in northwestern Patagonia. *Ecological Modelling*, **221(1)**, 113-121.

Giannakopoulos, C., P. Le Sager, M. Bindi, M. Moriondo, E. Kostopoulou, and C.M. Goodess, 2009: Climatic changes and associated impacts in the Mediterranean resulting from a 2 degrees C global warming. *Global and Planetary Change*, **68(3)**, 209-224.

Gibson, D.J. and L.C. Hulbert, 1987: Effects of fire, topography and year-to-year climatic variation on species composition in tallgrass prairie. *Vegetatio*, **72(3)**, 175-185.

Gibson, L., T.M. Lee, L.P. Koh, B.W. Brook, T.A. Gardner, J. Barlow, C.A. Peres, C.J.A. Bradshaw, W.F. Laurance, T.E. Lovejoy, and N.S. Sodhi, 2011: Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature*, **478(7369)**, 378- 381.

Gienapp, P., C. Teplitsky, J.S. Alho, J.A. Mills, and J. Merila, 2008: Climate change and evolution: disentangling environmental and genetic responses. *Molecular Ecology*, **17(1)**, 167-178.

Gienapp, P., M. Lof, T.E. Reed, J. McNamara, S. Verhulst, and M.E. Visser, 2013: Predicting demographically sustainable rates of adaptation: can great tit breeding time keep pace with climate change? *Philosophical Transactions of the Royal Society B*, **368(1610)**, 20120289, doi:10.1098/rstb.2012.0289.

Giglio, L., J.T. Randerson, and G.R. van der Werf, 2013: Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4). *Journal of Geophysical Research: Biogeosciences*, **118(1)**, 317-328.

Gilg, O., K.M. Kovacs, J. Aars, J. Fort, G. Gauthier, D. Gremillet, R.A. Ims, H. Meltofte, J. Moreau, E. Post, N.M. Schmidt, G. Yannic, and L. Bollache, 2012: Climate change and the ecology and evolution of Arctic vertebrates. In: *The Year in Ecology and Conservation Biology 2012* [Ostfeld, R.S. and W.H. Schlesinger (eds.)]. Vol. 102 of the Annals of the New York Academy of Sciences, Wiley-Blackwell Publishing (for the New York Academy of Science), Boston, MA, USA, pp. 166-190.

Gill, A.M., J.Z. Wionarski, and A. York, 1999: *Australians Biodiversity Responses to Fire: Plants, Birds and Invertebrates*. Commonwealth Department of the Environment and Heritage, Canberra, Australia, 267 pp.

Gill, J.L., J.W. Williams, S.T. Jackson, K.B. Lininger, and G.S. Robinson, 2009: Pleistocene megafaunal collapse, novel plant communities, and enhanced fire regimes in North America. *Science*, **326(5956)**, 1100-1103.

Gillingham, P.K., B. Huntley, W.E. Kunin, and C.D. Thomas, 2012: The effect of spatial resolution on projected responses to climate warming. *Diversity and Distributions*, **18(10)**, 990-1000.

Gilman, S.E., M.C. Urban, J. Tewksbury, G.W. Gilchrist, and R.D. Holt, 2010: A framework for community interactions under climate change. *Trends in Ecology & Evolution*, **25(6)**, 325-331.

Giorgi, F. and P. Lionello, 2008: Climate change projections for the Mediterranean region. *Global and Planetary Change*, **63(2-3)**, 90-104.

Girardin, M.P. and M. Mudelsee, 2008: Past and future changes in Canadian boreal wildfire activity. *Ecological Applications*, **18(2)**, 391-406.

Girardin, M.P., A.A. Ali, C. Carcaillet, M. Mudelsee, I. Drobyshev, C. Hely, and Y. Bergeron, 2009: Heterogeneous response of circumboreal wildfire risk to climate change since the early 1900s. *Global Change Biology*, **15(11)**, 2751-2769.

Girardin, M.P., P.Y. Bernier, and S. Gauthier, 2011: Increasing potential NEP of eastern boreal North American forests constrained by decreasing wildfire activity. *Ecosphere*, **2**, 25, doi:10.1890/ES10-00159.1.

Girardin, M.P., X.J. Guo, P.Y. Bernier, F. Raulier, and S. Gauthier, 2012: Changes in growth of pristine boreal North American forests from 1950 to 2005 driven by landscape demographics and species traits. *Biogeosciences*, **9(7)**, 2523-2536.

Girardin, M.P., A.A. Ali, C. Carcaillet, S. Gauthier, C. Hely, H. Le Goff, A. Terrier, and Y. Bergeron, 2013a: Fire in managed forests of eastern Canada: risks and options. *Forest Ecology and Management*, **294**, 238-249.

Girardin, M.P., A.A. Ali, C. Carcaillet, O. Blarquez, C. Hely, A. Terrier, A. Genries, and Y. Bergeron, 2013b: Vegetation limits the impact of a warm climate on boreal wildfires. *New Phytologist*, **199(4)**, 1001-1011.

Goetz, S.J., M.C. Mack, K.R. Gurney, J.T. Randerson, and R.A. Houghton, 2007: Ecosystem responses to recent climate change and fire disturbance at northern high latitudes: observations and model results contrasting northern Eurasia and North America. *Environmental Research Letters*, **2(4)**, 045031, doi:10.1088/1748-9326/2/4/045031.

Goetz, S.J., H.E. Epstein, U. Bhatt, G.J. Jia, J.O. Kaplan, H. Lischke, Q. Yu, A. Bunn, A. Lloyd, D. Alcaraz, P.S.A. Beck, J. Comiso, M.K. Raynolds, and D.A. Walker, 2011: Recent changes in Arctic vegetation: satellite observations and simulation model predictions. In: *Eurasian Arctic Land Cover and Land Use in a Changing Climate* [Gutman, G. and A. Reissell (eds.)]. Springer-Verlag, Amsterdam, Netherlands, pp. 9-36.

Goldblum, D. and L.S. Rigg, 2010: The deciduous forest – boreal forest ecotone. *Geography Compass*, **4(7)**, 701-717.

Golding, N. and R. Betts, 2008: Fire risk in Amazonia due to climate change in the HadCM3 climate model: potential interactions with deforestation. *Global Biogeochemical Cycles*, **22(4)**, GB4007, doi:10.1029/2007GB003166.

Gonzalez, P., 2001: Desertification and a shift of forest species in the West African Sahel. *Climate Research*, **17(2)**, 217-228.

Gonzalez, P., R.P. Neilson, J.M. Lenihan, and R.J. Drapek, 2010: Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change. *Global Ecology and Biogeography*, **19(6)**, 755-768.

Gonzalez, P., C.J. Tucker, and H. Sy, 2012: Tree density and species decline in the African Sahel attributable to climate. *Journal of Arid Environments*, **78(0)**, 55-64.

Good, P., C. Jones, J. Lowe, R. Betts, B. Booth, and C. Huntingford, 2011a: Quantifying environmental drivers of future tropical forest extent. *Journal of Climate*, **24(5)**, 1337-1349.

Good, P., J. Caesar, D. Bernie, J.A. Lowe, P. van der Linden, S.N. Gosling, R. Warren, N.W. Arnell, S. Smith, J. Bamber, T. Payne, S. Laxon, M. Srokosz, S. Sitch, N. Gedney, G. Harris, H. Hewitt, L. Jackson, C.D. Jones, F. O'Connor, J. Ridley, M. Vellinga, P. Halloran, and D. McNeall, 2011b: A review of recent developments in climate change science. Part I: understanding of future change in the large-scale climate system. *Progress in Physical Geography*, **35(3)**, 281-296.

Good, P., C. Jones, J. Lowe, R. Betts, and N. Gedney, 2013: Comparing tropical forest projections from two generations of Hadley Centre Earth System Models, HadGEM2-ES and HadCM3LC. *Journal of Climate*, **26(2)**, 495-511.

Gordo, O., 2007: Why are bird migration dates shifting? A review of weather and climate effects on avian migratory phenology. *Climate Research*, **35(1-2)**, 37-58.

Gordo, O. and J.J. Sanz, 2005: Phenology and climate change: a long-term study in a Mediterranean locality. *Oecologia*, **146(3)**, 484-495.

Gordo, O. and J.J. Sanz, 2010: Impact of climate change on plant phenology in Mediterranean ecosystems. *Global Change Biology*, **16(3)**, 1082-1106.

Gottfried, M., H. Pauli, A. Futschik, M. Akhalkatsi, P. Barancok, J.L.B. Alonso, G. Coldea, J. Dick, B. Erschbamer, M.R.F. Calzado, G. Kazakis, J. Krajci, P. Larsson, M. Mallaun, O. Michelsen, D. Moiseev, P. Moiseev, U. Molau, A. Merzouki, L. Nagy, G. Nakhutsrishvili, B. Pedersen, G. Pelino, M. Puscas, G. Rossi, A. Stanisci, J.P. Theurillat, M. Tomaselli, L. Villar, P. Vittoz, I. Vogiatzakis, and G. Grabherr, 2012: Continent-wide response of mountain vegetation to climate change. *Nature Climate Change*, **2(2)**, 111-115.

Graiprab, P., K. Pongput, N. Tangtham, and P.W. Gassman, 2010: Hydrologic evaluation and effect of climate change on the At Samat watershed, Northeastern Region, Thailand. *International Agricultural Engineering Journal*, **19(2)**, 12-22.

Green, R.E., Y.C. Collingham, S.G. Willis, R.D. Gregory, K.W. Smith, and B. Huntley, 2008: Performance of climate envelope models in retrodicting recent changes in bird population size from observed climatic change. *Biology Letters*, **4(5)**, 599-602.

Griesbauer, H.P. and D.S. Green, 2012: Geographic and temporal patterns in white spruce climate – growth relationships in Yukon, Canada. *Forest Ecology and Management*, **267**, 215-227.

Grime, J.P., J.D. Fridley, A.P. Askew, K. Thompson, J.G. Hodgson, and C.R. Bennet, 2008: Long-term resistance to simulated climate change in an infertile grassland. *Proceedings of the National Academy of Sciences of the United States of America*, **105(29)**, 10028-10032.

Groisman, P.Y., R.W. Knight, and T.R. Karl, 2012: Changes in intense precipitation over the central United States. *Journal of Hydrometeorology*, **13(1)**, 47-66.

Grosse, G., J. Harden, M. Turetsky, A.D. McGuire, P. Camill, C. Tarnocai, S. Frolking, E.A.G. Schuur, T. Jorgenson, S. Marchenko, V. Romanovsky, K.P. Wickland, N. French, M. Waldrop, L. Bourgeau-Chavez, and R.G. Striegl, 2011: Vulnerability of high-latitude soil organic carbon in North America to disturbance. *Journal of Geophysical Research: Biogeosciences*, **116(G4)**, G00K06, doi:10.1029/2010JG001507.

Gruber, N. and J.N. Galloway, 2008: An Earth-system perspective of the global nitrogen cycle. *Nature*, **451(7176)**, 293-296.

Guglielmin, M. and N. Cannone, 2012: A permafrost warming in a cooling Antarctica? *Climatic Change*, **111(2)**, 177-195.

Gunderson, A.R. and M. Leal, 2012: Geographic variation in vulnerability to climate warming in a tropical Caribbean lizard. *Functional Ecology*, **26(4)**, 783-793.

Gunderson, C.A., N.T. Edwards, A.V. Walker, K.H. O'Hara, C.M. Campion, and P.J. Hanson, 2012: Forest phenology and a warmer climate – growing season extension in relation to climatic provenance. *Global Change Biology*, **18(6)**, 2008-2025.

Gunderson, L. and C.S. Holling (eds.), 2001: *Panarchy: Understanding Transformations in Systems of Humans and Nature*. Island Press, Washington, DC, USA, 507 pp.

Gyllström, M., L.A. Hansson, E. Jeppesen, F. Garcia-Criado, E. Gross, K. Irvine, T. Kairesalo, R. Kornijow, M.R. Miracle, M. Nykanen, T. Noges, S. Romo, D. Stephen, E. Van Donk, and B. Moss, 2005: The role of climate in shaping zooplankton communities of shallow lakes. *Limnology and Oceanography*, **50(6)**, 2008-2021.

Haberl, H., K.H. Erb, F. Krausmann, A. Bondeau, C. Lauk, C. Müller, C. Plutzar, and J.K. Steinberger, 2011: Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. *Biomass and Bioenergy*, **35(12)**, 4753-4769.

Hague, M.J., M.R. Ferrari, J.R. Miller, D.A. Patterson, G.L. Russell, A.P. Farrell, and S.G. Hinch, 2011: Modelling the future hydroclimatology of the lower Fraser River and its impacts on the spawning migration survival of sockeye salmon. *Global Change Biology*, **17(1)**, 87-98.

Haider, S., C. Kueffer, P.J. Edwards, and J.M. Alexander, 2012: Genetically based differentiation in growth of multiple non-native plant species along a steep environmental gradient. *Oecologia*, **170(1)**, 89-99.

Hall, J.S., M.S. Ashton, E.J. Garen, and S. Jose, 2011: The ecology and ecosystem services of native trees: implications for reforestation and land restoration in Mesoamerica. *Forest Ecology and Management*, **261(10)**, 1553-1557.

Halley, J.M., Y. Iwasa, and D. Vokou, 2013: Comment on "Extinction debt and windows of conservation opportunity in the Brazilian Amazon". *Science*, **339(6117)**, 271.

Hamilton, S.K., 2010: Biogeochemical implications of climate change for tropical rivers and floodplains. *Hydrobiologia*, **657(1)**, 19-35.

Hampe, A., 2011: Plants on the move: the role of seed dispersal and initial population establishment for climate-driven range expansions. *Acta Oecologica: International Journal of Ecology*, **37(6)**, 666-673.

Hannah, L., 2012: *Saving a Million Species: Extinction Risk from Climate Change*. Island Press, Washington, DC, USA, 419 pp.

Hannah, L., G. Midgley, S. Andelman, M. Araujo, G. Hughes, E. Martinez-Meyer, R. Pearson, and P. Williams, 2007: Protected area needs in a changing climate. *Frontiers in Ecology and the Environment*, **5(3)**, 131-138.

Hansen, M.M., I. Olivieri, D.M. Waller, E.E. Nielsen, and The GeM Working Group, 2012: Monitoring adaptive genetic responses to environmental change. *Molecular Ecology*, **21(6)**, 1311-1329.

Hari, P. and L. Kulmata, 2008: *Boreal Forest and Climate Change*. Springer, New York, NY, USA, 582 pp.

Harris, J.A., R.J. Hobbs, E. Higgs, and J. Aronson, 2006: Ecological restoration and global climate change. *Restoration Ecology*, **14**, 170-176.

Harrison, S.P. and M.F.S. Goni, 2010: Global patterns of vegetation response to millennial-scale variability and rapid climate change during the last glacial period. *Quaternary Science Reviews*, **29(21-22)**, 2957-2980.

Harsch, M.A., P.E. Hulme, M.S. McGlone, and R.P. Duncan, 2009: Are treelines advancing? A global meta-analysis of treeline response to climate warming. *Ecology Letters*, **12(10)**, 1040-1049.

Hastings, A., 2004: Transients: the key to long-term ecological understanding? *Trends in Ecology & Evolution*, **19(1)**, 39-45.

Haxeltine, A. and I.C. Prentice, 1996: BIOME3: an equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability, and competition among plant functional types. *Global Biogeochemical Cycles*, **10**, 693-709.

Hayes, F., M.L.M. Jones, G. Mills, and M. Ashmore, 2007: Meta-analysis of the relative sensitivity of semi-natural vegetation species to ozone. *Environmental Pollution*, **146(3)**, 754-762.

Hayes, K.R. and S.C. Barry, 2008: Are there any consistent predictors of invasion success? *Biological Invasions*, **10(4)**, 483-506.

Haywood, A.M. and P.J. Valdes, 2006: Vegetation cover in a warmer world simulated using a dynamic global vegetation model for the Mid-Pliocene. *Palaeogeography Palaeoclimatology Palaeoecology*, **237(2-4)**, 412-427.

Haywood, A.M., A. Ridgwell, D.J. Lunt, D.J. Hill, M.J. Pound, H.J. Dowsett, A.M. Dolan, J.E. Francis, and M. Williams, 2011: Are there pre-Quaternary geological analogues for a future greenhouse warming? *Philosophical Transactions of the Royal Society A*, **369(1938)**, 933-956.

Heckenberger, M.J., J.C. Russell, J.R. Toney, and M.J. Schmidt, 2007: The legacy of cultural landscapes in the Brazilian Amazon: implications for biodiversity. *Philosophical Transactions of the Royal Society B*, **362(1478)**, 197-208.

Hegarty, M.J., 2012: Invasion of the hybrids. *Molecular Ecology*, **21(19)**, 4669-4671.

Hegglin, M.I. and T.G. Shepherd, 2009: Large climate-induced changes in ultraviolet index and stratosphere-to-troposphere ozone flux. *Nature Geoscience*, **10(10)**, 687- 691.

Hegland, S.J., A. Nielsen, A. Lazaro, A.L. Bjerknes, and Totland, 2009: How does climate warming affect plant-pollinator interactions? *Ecology Letters*, **12(2)**, 184-195.

Hejcman, M., P. Hejcmanova, V. Pavlu, and J. Benes, 2013: Origin and history of grasslands in Central Europe – a review. *Grass and Forage Science*, **68(3)**, 345-363.

Hellden, U. and C. Tottrup, 2008: Regional desertification: a global synthesis. *Global and Planetary Change*, **64(3-4)**, 169-176.

Heller, N.E. and E.S. Zavaleta, 2009: Biodiversity management in the face of climate change: a review of 22 years of recommendations. *Biological Conservation*, **142(1)**, 14-32.

Hellmann, J.J., J.E. Byers, B.G. Bierwagen, and J.S. Dukes, 2008: Five potential consequences of climate change for invasive species. *Conservation Biology*, **22(3)**, 534-543.

Hemery, G.E., 2008: Forest management and silvicultural responses to projected climate change impacts on European broadleaved trees and forests. *International Forestry Review*, **10(4)**, 591-607.

Hendry, A.P. and A. Gonzalez, 2008: Whither adaptation? *Biology & Philosophy*, **23(5)**, 673-699.

Hermoso, V. and M. Clavero, 2011: Threatening processes and conservation management of endemic freshwater fish in the Mediterranean basin: a review. *Marine and Freshwater Research*, **62(3)**, 244-254.

Hewitt, N., N. Klenk, A.L. Smith, D.R. Bazely, N. Yan, S. Wood, J.I. MacLellan, C. Lipsig-Mumme, and I. Henriques, 2011: Taking stock of the assisted migration debate. *Biological Conservation*, **144(11)**, 2560-2572.

Hickler, T., B. Smith, I.C. Prentice, K. Mjöfors, P. Miller, A. Arneth, and M.T. Sykes, 2008: CO_2 fertilization in temperate FACE experiments not representative of boreal and tropical forests. *Global Change Biology*, **14**, 1531-1542.

Hickler, T., K. Vohland, J. Feehan, P.A. Miller, B. Smith, L. Costa, T. Giesecke, S. Fronzek, T.R. Carter, W. Cramer, I. Kühn, and M.T. Sykes, 2012: Projecting the future distribution of European potential natural vegetation zones with a generalized, tree species-based dynamic vegetation model. *Global Ecology and Biogeography*, **21(1)**, 50-63.

Hickling, R., D.B. Roy, J.K. Hill, R. Fox, and C.D. Thomas, 2006: The distributions of a wide range of taxonomic groups are expanding polewards. *Global Change Biology*, **12(3)**, 450-455.

Higgins, S.I. and S. Scheiter, 2012: Atmospheric CO_2 forces abrupt vegetation shifts locally, but not globally. *Nature*, **488(7410)**, 209-212.

Higgins, S.I., J.S. Clark, R. Nathan, T. Hovestadt, F. Schurr, J.M.V. Fragoso, M.R. Aguiar, E. Ribbens, and S. Lavorel, 2003: Forecasting plant migration rates: managing uncertainty for risk assessment. *Journal of Ecology*, **91(3)**, 341-347.

Higgins, S.I., R.B. O'Hara, and C. Romermann, 2012: A niche for biology in species distribution models. *Journal of Biogeography*, **39(12)**, 2091-2095.

Higuera, P.E., M.L. Chipman, J.L. Barnes, M.A. Urban, and F.S. Hu, 2011: Variability of tundra fire regimes in Arctic Alaska: millennial-scale patterns and ecological implications. *Ecological Applications*, **21(8)**, 3211-3226.

Hijioka, Y., Y. Matsuoka, H. Nishimoto, and M. Kainuma, (2008): Global GHG emission scenrios under GHG concentration stabilization targets. *Journal of Global Environmental Engineering*, **13**, 97-108.

Hill, P.W., J. Farrar, P. Roberts, M. Farrell, H. Grant, K.K. Newsham, D.W. Hopkins, R.D. Bardgett, and D.L. Jones, 2011: Vascular plant success in a warming Antarctic may be due to efficient nitrogen acquisition. *Nature Climate Change*, **1(1)**, 50-53.

Hinzman, L.D., N.D. Bettez, W.R. Bolton, F.S. Chapin III, M.B. Dyurgerov, C.L. Fastie, B. Griffith, R.D. Hollister, A. Hope, H.P. Huntington, A.M. Jensen, G.J. Jia, T. Jorgenson, D.L. Kane, D.R. Klein, G. Kofinas, A.H. Lynch, A.H. Lloyd, A.D. McGuire, F.E. Nelson, W.C. Oechel, T.E. Osterkamp, C.H. Racine, V.E. Romanovsky, R.S. Stone, D.A. Stow, M. Sturm, C.E. Tweedie, G.L. Vourlitis, M.D. Walker, D.A. Walker, P.J. Webber, J.M. Welker, K. Winker, and K. Yoshikawa, 2005: Evidence and implications of recent climate change in northern Alaska and other arctic regions. *Climatic Change*, **72(3)**, 251-298.

Hockey, P.A.R., C. Sirami, A.R. Ridley, G.F. Midgley, and H.A. Babiker, 2011: Interrogating recent range changes in South African birds: confounding signals from land use and climate change present a challenge for attribution. *Diversity and Distributions*, **17(2)**, 254-261.

Hodgson, J.A., C.D. Thomas, C. Dytham, J.M.J. Travis, and S.J. Cornell, 2012: The speed of range shifts in fragmented landscapes. *PLoS One*, **7(10)**, e47141, doi:10.1371/journal.pone.0047141.

Hoegh-Guldberg, O., L. Hughes, S. McIntyre, D.B. Lindenmayer, C. Parmesan, H.P. Possingham, and C.D. Thomas, 2008: Assisted colonization and rapid climate change. *Science*, **321(5887)**, 345-346.

Hof, C., M.B. Araujo, W. Jetz, and C. Rahbek, 2011a: Additive threats from pathogens, climate and land-use change for global amphibian diversity. *Nature*, **480(7378)**, 516-519.

Hof, C., I. Levinsky, M.B. Araujo, and C. Rahbek, 2011b: Rethinking species' ability to cope with rapid climate change. *Global Change Biology*, **17(9)**, 2987-2990.

Hoffmann, A.A. and C.M. Sgro, 2011: Climate change and evolutionary adaptation. *Nature*, **470(7335)**, 479-485.

Hoffmann, M., C. Hilton-Taylor, A. Angulo, M. Bohm, T.M. Brooks, S.H.M. Butchart, K.E. Carpenter, J. Chanson, B. Collen, N.A. Cox, W.R.T. Darwall, N.K. Dulvy, L.R. Harrison, V. Katariya, C.M. Pollock, S. Quader, N.I. Richman, A.S.L. Rodrigues, M.F. Tognelli, J.C. Vie, J.M. Aguiar, D.J. Allen, G.R. Allen, G. Amori, N.B. Ananjeva, F. Andreone, P. Andrew, A.L.A. Ortiz, J.E.M. Baillie, R. Baldi, B.D. Bell, S.D. Biju, J.P. Bird, P. Black-Decima, J.J. Blanc, F. Bolanos, W. Bolivar, I.J. Burfield, J.A. Burton, D.R. Capper, F. Castro, G. Catullo, R.D. Cavanagh, A. Channing, N.L. Chao, A.M. Chenery, F. Chiozza, V. Clausnitzer, N.J. Collar, L.C. Collett, B.B. Collette, C.F.C. Fernandez, M.T. Craig, M.J. Crosby, N. Cumberlidge, A. Cuttelod, A.E. Derocher, A.C. Diesmos, J.S. Donaldson, J.W. Duckworth, G. Dutson, S.K. Dutta, R.H. Emslie, A. Farjon, S. Fowler, J. Freyhof, D.L. Garshelis, J. Gerlach, D.J. Gower, T.D. Grant, G.A. Hammerson, R.B. Harris, L.R. Heaney, S.B. Hedges, J.M. Hero, B. Hughes, S.A. Hussain, J. Icochea, R.F. Inger, N. Ishii, D.T. Iskandar, R.K.B. Jenkins, Y. Kaneko, M. Kottelat, K.M. Kovacs, S.L. Kuzmin, E. La Marca, J.F. Lamoreux, M.W.N. Lau, E.O. Lavilla, K. Leus, R.L. Lewison, G. Lichtenstein, S.R. Livingstone, V. Lukoschek, D.P. Mallon, P.J.K. McGowan, A. McIvor, P.D. Moehlman, S. Molur, A.M. Alonso, J.A. Musick, K. Nowell, R.A. Nussbaum, W. Olech, N.L. Orlov, T.J. Papenfuss, G. Parra-Olea, W.F. Perrin, B.A. Polidoro, M. Pourkazemi, P.A. Racey, J.S. Ragle, M. Ram, G. Rathbun, R.P. Reynolds, A.G.J. Rhodin, S.J. Richards, L.O. Rodriguez, S.R. Ron, C. Rondinini, A.B. Rylands, Y.S. de Mitcheson, J.C. Sanciangco, K.L. Sanders, G. Santos-Barrera, J. Schipper, C. Self-Sullivan, Y.C. Shi, A. Shoemaker, F.T. Short, C. Sillero-Zubiri, D.L. Silvano, K.G. Smith, A.T. Smith, J. Snoeks, A.J. Stattersfield, A.J. Symes, A.B. Taber, B.K. Talukdar, H.J. Temple, R. Timmins, J.A. Tobias, K. Tsytsulina, D. Tweddle, C. Ubeda, S.V. Valenti, P.P. van Dijk, L.M. Veiga, A. Veloso, D.C. Wege, M. Wilkinson, E.A. Williamson, F. Xie, B.E. Young, H.R. Akcakaya, L. Bennun, T.M. Blackburn, L. Boitani, H.T. Dublin, G.A.B. da Fonseca, C. Gascon, T.E. Lacher, G.M. Mace, S.A. Mainka, J.A. McNeely, R.A. Mittermeier, G.M. Reid, J.P. Rodriguez, A.A. Rosenberg, M.J. Samways, J. Smart, B.A. Stein, and S.N. Stuart, 2010: The impact of conservation on the status of the World's vertebrates. *Science*, **330(6010)**, 1503-1509.

Hofmann, G.E. and A.E. Todgham, 2010: Living in the now: physiological mechanisms to tolerate a rapidly changing environment. *Annual Review of Physiology*, **72**, 127-145.

Hofmockel, K.S., D.R. Zak, K.K. Moran, and J.D. Jastrow, 2011: Changes in forest soil organic matter pools after a decade of elevated CO_2 and O_3. *Soil Biology and Biochemistry*, **43(7)**, 1518-1527.

Hogg, E.H., J.P. Brandt, and M. Michaelian, 2008: Impact of a regional drought on the productivity, dieback and biomass of western Canadian aspen forests. *Canadian Journal of Forest Research / Revue Canadienne De Recherche Forestiere*, **38**, 1373-1384.

Hole, D.G., S.G. Willis, D.J. Pain, L.D. Fishpool, S.H.M. Butchart, Y.C. Collingham, C. Rahbek, and B. Huntley, 2009: Projected impacts of climate change on a continent-wide protected area network. *Ecology Letters*, **12(5)**, 420-431.

Hole, D.G., B. Huntley, J. Arinaitwe, S.H.M. Butchart, Y.C. Collingham, L.D.C. Fishpool, D.J. Pain, and S.G. Willis, 2011: Toward a management framework for networks of protected areas in the face of climate change. *Conservation Biology*, **25(2)**, 305-315.

Holmgren, M., P. Stapp, C.R. Dickman, C. Gracia, S. Graham, J.R. Gutiérrez, C. Hice, F. Jaksic, D.A. Kelt, M. Letnic, M. Lima, B.C. López, P.L. Meserve, W.B. Milstead, G.A. Polis, M.A. Previtali, M. Richter, S. Sabaté, and F.A. Squeo, 2006: Extreme climatic events shape arid and semiarid ecosystems. *Frontiers in Ecology and the Environment*, **4(2)**, 87-95.

Hongve, D., G. Riise, and J.F. Kristiansen, 2004: Increased colour and organic acid concentrations in Norwegian forest lakes and drinking water – a result of increased precipitation? *Aquatic Sciences*, **66(2)**, 231-238.

Hooijer, A., S. Page, J.G. Canadell, M. Silvius, J. Kwadijk, H. Wosten, and J. Jauhiainen, 2010: Current and future CO_2 emissions from drained peatlands in Southeast Asia. *Biogeosciences*, **7(5)**, 1505-1514.

Hoover, S.E.R., J.J. Ladley, A.A. Shchepetkina, M. Tisch, S.P. Gieseg, and J.M. Tylianakis, 2012: Warming, CO_2, and nitrogen deposition interactively affect a plant-pollinator mutualism. *Ecology Letters*, **15(3)**, 227-234.

Horowitz, L.W., 2006: Past present and future concentrations of tropospheric ozone and aerosols: morthodology, ozone evaluation, and sensitivity to aerosol wet removal. *Journal of Geophysical Research: Atmospheres*, **111(D22)**, D22211, doi:10.1029/2005JD006937 .

Hosonuma, N., M. Herold, V. De Sy, R.S. De Fries, M. Brockhaus, L. Verchot, A. Angelsen, and E. Romijn, 2012: An assessment of deforestation and forest degradation drivers in developing countries. *Environmental Research Letters*, **7(4)**, 044009, doi:10.1088/1748-9326/7/4/044009.

Høye, T.T., E. Post, H. Meltofte, N.M. Schmidt, and M.C. Forchhammer, 2007: Rapid advancement of spring in the High Arctic. *Current Biology*, **17(12)**, R449-R451.

Hoyle, C.R., M. Boy, N.M. Donahue, J.L. Fry, M. Glasius, A. Guenther, A.G. Hallar, K.H. Hartz, M.D. Petters, T. Petaja, T. Rosenoern, and A.P. Sullivan, 2011: A review of the anthropogenic influence on biogenic secondary organic aerosol. *Atmospheric Chemistry and Physics*, **11(1)**, 321-343.

Huang, D., R.A. Haack, and R. Zhang, 2011: Does global warming increase establishment rates of invasive alien species? A Centurial time series analysis. *PLoS One*, **6(9)**, doi:10.1371/journal.pone.0024733.

Huang, J.G., Y. Bergeron, B. Denneler, F. Berninger, and J. Tardif, 2007: Response of forest trees to increased atmospheric CO_2. *Critical Reviews in Plant Sciences*, **26(5-6)**, 265-283.

Huey, R.B., M.R. Kearney, A. Krockenberger, J.A.M. Holtum, M. Jess, and S.E. Williams, 2012: Predicting organismal vulnerability to climate warming: roles of behaviour, physiology and adaptation. *Philosophical Transactions of the Royal Society B*, **367(1596)**, 1665-1679.

Hughes, R.F., S.R. Archer, G.P. Asner, C.A. Wessman, C.H.A.D. McMurtry, J.I.M. Nelson, and R.J. Ansley, 2006: Changes in aboveground primary production and carbon and nitrogen pools accompanying woody plant encroachment in a temperate savanna. *Global Change Biology*, **12(9)**, 1733-1747.

Hughes, T.P., C. Linares, V. Dakos, I.A. van de Leemput, and E.H. van Nes, 2013: Living dangerously on borrowed time during slow, unrecognized regime shifts. *Trends in Ecology & Evolution*, **28(3)**, 149-155.

Hülber, K., M. Winkler, and G. Grabherr, 2010: Intraseasonal climate and habitat-specific variability controls the flowering phenology of high alpine plant species. *Functional Ecology*, **24(2)**, 245-252.

Hunt, A. and P. Watkiss, 2011: Climate change impacts and adaptation in cities: a review of the literature. *Climatic Change*, **104(1)**, 13-49.

Hunter, C.M., H. Caswell, M.C. Runge, E.V. Regehr, S.C. Amstrup, and I. Stirling, 2010: Climate change threatens polar bear populations: a stochastic demographic analysis. *Ecology*, **91(10)**, 2883-2897.

Huntingford, C., P.M. Cox, L.M. Mercado, S. Sitch, N. Bellouin, O. Boucher, and N. Gedney, 2011: Highly contrasting effects of different climate forcing agents on terrestrial ecosystem services. *Philosophical Transactions of the Royal Society A*, **369(1943)**, 2026-2037.

Huntingford, C., P. Zelazowski, D. Galbraith, L.M. Mercado, S. Sitch, R. Fisher, M. Lomas, A. P.Walker, C.D. Jones, B.B.B. Booth, Y. Malhi, D. Hemming, G. Kay, P. Good, S.L. Lewis, O.L. Phillips, O.K. Atkin, J. Lloyd, E. Gloor, J. Zaragoza-Castells, P. Meir, R. Betts, P.P. Harris, C. Nobre, J. Marengo, and P.M. Cox, 2013: Simulated resilience of tropical rainforests to CO_2-induced climate change. *Nature Geoscience*, **6**, 268-273.

Huntington, T.G., 2008: CO_2-induced suppression of transpiration cannot explain increasing runoff. *Hydrological Processes*, **22(2)**, 311-314.

Hurtt, G.C., L.P. Chini, S. Frolking, R.A. Betts, J. Feddema, G. Fischer, J.P. Fisk, K. Hibbard, R.A. Houghton, A. Janetos, C.D. Jones, G. Kindermann, T. Kinoshita, K.K. Goldewijk, K. Riahi, E. Shevliakova, S. Smith, E. Stehfest, A. Thomson, P. Thornton, D.P.v. Vuuren, and Y.P. Wang, 2011: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. *Climatic Change*, **109**, 117-161.

Husby, A., M.E. Visser, and L.E.B. Kruuk, 2011: Speeding up microevolution: the effects of increasing temperature on selection and genetic variance in a wild bird population. *PLoS Biology*, **9(2)**, e1000585, doi:10.1371/journal.pbio.1000585.

Ihlow, F., J. Dambach, J.O. Engler, M. Flecks, T. Hartmann, S. Nekum, H. Rajaei, and D. Rodder, 2012: On the brink of extinction? How climate change may affect global chelonian species richness and distribution. *Global Change Biology*, **18(5)**, 1520-1530.

Innes, J.L., 1992: Observations on the condition of beech (*Fagus sylvatica* L.) in Britain in 1990. *Forestry*, **65(1)**, 35-60.

Inouye, D.W., 2008: Effects of climate change on phenology, frost damage, and floral abundance of montane wildflowers. *Ecology*, **89(2)**, 353-362.

INPE, 2013: *Projeto Desmatamento (PRODES): Monitoramento da Floresta Amazonica por Satelite*. Cited 2013, www.obt.inpe.br/prodes/.

IPCC, 2012: Summary for policymakers. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3-21.

Iverson, L.R., M.W. Schwartz, and A.M. Prasad, 2004: How fast and far might tree species migrate in the eastern United States due to climate change? *Global Ecology and Biogeography*, **13(3)**, 209-219.

Iverson, L.R., A. Prasad, and S. Matthews, 2008: Modeling potential climate change impacts on the trees of the northeastern United States. *Mitigation and Adaptation Strategies for Global Change*, **13(5-6)**, 487-516.

Iverson, L.R., A.M. Prasad, S.N. Matthews, and M.P. Peters, 2011: Lessons learned while integrating habitat, dispersal, disturbance, and life-history traits into species habitat models under climate change. *Ecosystems*, **14(6)**, 1005-1020.

Jackson, R.B., E.G. Jobbagy, R. Avissar, S.B. Roy, D.J. Barrett, C.W. Cook, K.A. Farley, D.C. le Maitre, B.A. McCarl, and B.C. Murray, 2005: Trading water for carbon with biological sequestration. *Science*, **310(5756)**, 1944-1947.

Jackson, S.T. and R.J. Hobbs, 2009: Ecological restoration in the light of ecological history. *Science*, **325(5940)**, 567-569.

Jackson, S.T. and J.T. Overpeck, 2000: Responses of plant populations and communities to environmental changes of the Late Quaternary. *Paleobiology*, **26(4)**, 194-220.

Jackson, S.T., S.T. Gray, and B. Shuman, 2009: Paleoecology and resource management in a dynamic landscape: case studies from the Rocky Mountain headwaters. In: *Conservation Paleobiology: Using the Past to Manage for the Future* [Dietl, G.P. and K.W. Flessa (eds.)]. The Paleontological Society Papers, Vol. 15, Boulder, CO, USA, pp. 61-80.

Jacobsen, D., A.M. Milner, L.E. Brown, and O. Dangles, 2012: Biodiversity under threat in glacier-fed river systems. *Nature Climate Change*, **2(5)**, 361-364.

Jamieson, M.A., A.M. Trowbridge, K.F. Raffa, and R.L. Lindroth, 2012: Consequences of climate warming and altered precipitation patterns for plant-insect and multitrophic interactions. *Plant Physiology*, **160(4)**, 1719-1727.

Jansen, E., J. Overpeck, K.R. Briffa, J.-C. Duplessy, F. Joos, V. Masson-Delmotte, D. Olago, B. Otto-Bliesner, W.R. Peltier, S. Rahmstorf, R. Ramesh, D. Raynaud, D. Rind, O. Solomina, R. Villalba, and D. Zhang, 2007: Paleoclimate. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 433-497.

Jaramillo, C., D. Ochoa, L. Contreras, M. Pagani, H. Carvajal-Ortiz, L.M. Pratt, S. Krishnan, A. Cardona, M. Romero, L. Quiroz, G. Rodriguez, M.J. Rueda, F. de la Parra, S. Moron, W. Green, G. Bayona, C. Montes, O. Quintero, R. Ramirez, G. Mora, S. Schouten, H. Bermudez, R. Navarrete, F. Parra, M. Alvaran, J. Osorno, J.L. Crowley, V. Valencia, and J. Vervoort, 2010: Effects of rapid global warming at the Paleocene-Eocene boundary on neotropical vegetation. *Science*, **330(6006)**, 957-961.

Jarvis, P.G., 1976: The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. *Philosophical Transactions of the Royal Society B*, **273**, 593-610.

Jenerette, G.D., S.L. Harlan, W.L. Stefanov, and C.A. Martin, 2011: Ecosystem services and urban heat riskscape moderation: water, green spaces, and social inequality in Phoenix, AZ, USA. *Ecological Applications*, **21(7)**, 2637-2651.

Jenkins, K.M. and A.J. Boulton, 2007: Detecting impacts and setting restoration targets in arid-zone rivers: aquatic micro-invertebrate responses to reduced floodplain inundation. *Journal of Applied Ecology*, **44(4)**, 823-832.

Jensen, K.D., C. Beier, A. Michelsen, and B.A. Emmett, 2003: Effects of experimental drought on microbial processes in two temperate heathlands at contrasting water conditions. *Applied Soil Ecology*, **24(2)**, 165-176.

Jeong, S.J., C.H. Ho, H.J. Gim, and M.E. Brown, 2011: Phenology shifts at start vs. end of growing season in temperate vegetation over the Northern Hemisphere for the period 1982-2008. *Global Change Biology*, **17(7)**, 2385-2399.

Jia, B., Y. Ma, and K. Qiu, 2009: Dynamics of the vegetation coverage in recent 15 years in Yijinhuoluo County, Inner Mongolia, China. *Arid Land Geography*, **32(4)**, 481-487.

Jia, G.J., H.E. Epstein, and D.A. Walker, 2009: Vegetation greening in the Canadian Arctic related to decadal warming. *Journal of Environmental Monitoring*, **11(12)**, 2231-2238.

Jin, J., S. Lu, S. Li, and N.L. Miller, 2010: Impact of land use change on the local climate over the Tibetan Plateau. *Advances in Meteorology*, **2010**, 837480, doi:10.1155/2010/837480.

Jin, Y., J.T. Randerson, S.J. Goetz, P.S.A. Beck, M.M. Loranty, and M.L. Goulden, 2012: The influence of burn severity on postfire vegetation recovery and albedo change during early succession in North American boreal forests. *Journal of Geophysical Research: Biogeosciences*, **117(G1)**, G01036, doi:10.1029/2011JG001886.

Johanson, C.M. and Q. Fu, 2009: Hadley cell widening: model simulations versus observations. *Journal of Climate*, **22(10)**, 2713-2725.

Jöhnk, K.D., J. Huisman, J. Sharples, B. Sommeijer, P.M. Visser, and J.M. Stroom, 2008: Summer heatwaves promote blooms of harmful cyanobacteria. *Global Change Biology*, **14(3)**, 495-512.

Johnson, W.C., B.V. Millett, T. Gilmanov, R.A. Voldseth, G.R. Guntenspergen, and D.E. Naugle, 2005: Vulnerability of northern prairie wetlands to climate change. *Bioscience*, **55(10)**, 863-872.

Johnstone, J.F., T.N. Hollingsworth, F.S. Chapin, and M.C. Mack, 2010: Changes in fire regime break the legacy lock on successional trajectories in Alaskan boreal forest. *Global Change Biology*, **16(4)**, 1281-1295.

Jones, C., J. Lowe, S. Liddicoat, and R. Betts, 2009: Committed terrestrial ecosystem changes due to climate change. *Nature Geoscience*, **2(7)**, 484-487.

Jones, C.D., J.K. Hughes, N. Bellouin, S.C. Hardiman, G.S. Jones, J. Knight, S. Liddicoat, F.M. O'Connor, R.J. Andres, C. Bell, K.O. Boo, A. Bozzo, N. Butchart, P. Cadule, K.D. Corbin, M. Doutriaux-Boucher, P. Friedlingstein, J. Gornall, L. Gray, P.R. Halloran, G. Hurtt, W.J. Ingram, J.F. Lamarque, R.M. Law, M. Meinshausen, S. Osprey, E.J. Palin, L.P. Chini, T. Raddatz, M.G. Sanderson, A.A. Sellar, A. Schurer, P. Valdes, N. Wood, S. Woodward, M. Yoshioka, and M. Zerroukat, 2011: The HadGEM2-ES implementation of CMIP5 centennial simulations. *Geoscientific Model Development*, **4(3)**, 543-570.

Jones, M.C., S.R. Dye, J.K. Pinnegar, R. Warren, and W.W.L. Cheung, 2012: Modelling commercial fish distributions: prediction and assessment using different approaches. *Ecological Modelling*, **225**, 133-145.

Jongman, R.H.G., I.M. Bouwma, A. Griffioen, L. Jones-Walters, and A.M. Van Doorn, 2011: The Pan European Ecological Network: PEEN. *Landscape Ecology*, **26(3)**, 311-326.

Jonsson, B. and N. Jonsson, 2009: A review of the likely effects of climate change on anadromous Atlantic salmon *Salmo salar* and brown trout *Salmo trutta*, with particular reference to water temperature and flow. *Journal of Fish Biology*, **75(10)**, 2381-2447.

Jorgenson, M.T., V. Romanovsky, J. Harden, Y. Shur, J. O'Donnell, E.A.G. Schuur, M. Kanevskiy, and S. Marchenko, 2010: Resilience and vulnerability of permafrost to climate change. *Canadian Journal of Forest Research / Revue Canadienne De Recherche Forestiere*, **40(7)**, 1219-1236.

Joubert, D.F., A. Rothauge, and G.N. Smit, 2008: A conceptual model of vegetation dynamics in the semiarid Highland savanna of Namibia, with particular reference to bush thickening by Acacia mellifera. *Journal of Arid Environments*, **72(12)**, 2201-2210.

Jung, M., M. Reichstein, P. Ciais, S.I. Seneviratne, J. Sheffield, M.L. Goulden, G. Bonan, A. Cescatti, J.Q. Chen, R. de Jeu, A.J. Dolman, W. Eugster, D. Gerten, D. Gianelle, N. Gobron, J. Heinke, J. Kimball, B.E. Law, L. Montagnani, Q.Z. Mu, B. Mueller, K. Oleson, D. Papale, A.D. Richardson, O. Roupsard, S. Running, E. Tomelleri, N. Viovy, U. Weber, C. Williams, E. Wood, S. Zaehle, and K. Zhang, 2010: Recent decline in the global land evapotranspiration trend due to limited moisture supply. *Nature*, **467(7318)**, 951-954.

Kaiser, K.E., B.L. McGlynn, and R.E. Emanuel, 2012: Ecohydrology of an outbreak: mountain pine beetle impacts trees in drier landscape positions first. *Ecohydrology*, **6(3)**, 444-454.

Kane, J.M., K.A. Meinhardt, T. Chang, B.L. Cardall, R. Michalet, and T.G. Whitham, 2011: Drought-induced mortality of a foundation species (*Juniperus monosperma*) promotes positive afterlife effects in understory vegetation. *Plant Ecology*, **212(5)**, 733-741.

Kanniah, K.D., J. Beringer, P. North, and L. Hutley, 2012: Control of atmospheric particles on diffuse radiation and terrestrial plant productivity. *Progress in Physical Geography*, **36(2)**, 209-237.

Kappes, H. and P. Haase, 2012: Slow, but steady: dispersal of freshwater molluscs. *Aquatic Sciences*, **74(1)**, 1-14.

Karell, P., K. Ahola, T. Karstinen, J. Valkama, and J.E. Brommer, 2011: Climate change drives microevolution in a wild bird. *Nature Communications*, **2**, 208, doi:10.1038/ncomms1213.

Karlsson, J., P. Bystrom, J. Ask, P. Ask, L. Persson, and M. Jansson, 2009: Light limitation of nutrient-poor lake ecosystems. *Nature*, **460(7254)**, 506-509.

Karnosky, D.F., K.S. Pregitzer, D.R. Zak, M.E. Kubiske, G.R. Hendrey, D. Weinstein, M. Nosal, and K.E. Percy, 2005: Scaling ozone responses of forest trees to the ecosystem level in a changing climate. *Plant Cell and Environment*, **28(8)**, 965-981.

Kasischke, E.S., D.L. Verbyla, T.S. Rupp, A.D. McGuire, K.A. Murphy, R. Jandt, J.L. Barnes, E.E. Hoy, P.A. Duffy, M. Calef, and M.R. Turetsky, 2010: Alaska's changing fire regime – implications for the vulnerability of its boreal forests. *Canadian Journal of Forest Research / Revue Canadienne De Recherche Forestiere*, **40(7)**, 1313-1324.

Kasson, M.T. and W.H. Livingston, 2012: Relationships among beech bark disease, climate, radial growth response and mortality of American beech in northern Maine, USA. *Forest Pathology*, **42(3)**, 199-212.

Kaufman, D.S., D.P. Schneider, N.P. McKay, C.M. Ammann, R.S. Bradley, K.R. Briffa, G.H. Miller, B.L. Otto-Bliesner, J.T. Overpeck, B.M. Vinther, and Arctic Lakes 2k Project, 2009: Recent warming reverses long-term arctic cooling. *Science*, **325(5945)**, 1236-1239.

Kaushal, S.S., G.E. Likens, N.A. Jaworski, M.L. Pace, A.M. Sides, D. Seekell, K.T. Belt, D.H. Secor, and R.L. Wingate, 2010: Rising stream and river temperatures in the United States. *Frontiers in Ecology and the Environment*, **8(9)**, 461-466.

Kearney, M. and W. Porter, 2009: Mechanistic niche modelling: combining physiological and spatial data to predict species' ranges. *Ecology Letters*, **12(4)**, 334-350.

Kearney, M., W.P. Porter, C. Williams, S. Ritchie, and A.A. Hoffmann, 2009: Integrating biophysical models and evolutionary theory to predict climatic impacts on species' ranges: the dengue mosquito *Aedes aegypti* in Australia. *Functional Ecology*, **23(3)**, 528-538.

Kearney, M.R., B.A. Wintle, and W.P. Porter, 2010: Correlative and mechanistic models of species distribution provide congruent forecasts under climate change. *Conservation Letters*, **3(3)**, 203-213.

Keenan, T., J. Maria Serra, F. Lloret, M. Ninyerola, and S. Sabate, 2011: Predicting the future of forests in the Mediterranean under climate change, with niche- and process-based models: CO_2 matters! *Global Change Biology*, **17(1)**, 565-579.

Keith, D.A., H.R. Akcakaya, W. Thuiller, G.F. Midgley, R.G. Pearson, S.J. Phillips, H.M. Regan, M.B. Araujo, and T.G. Rebelo, 2008: Predicting extinction risks under climate change: coupling stochastic population models with dynamic bioclimatic habitat models. *Biology Letters*, **4(5)**, 560-563.

Keith, H., E. van Gorsel, K.L. Jacobsen, and H.A. Cleugh, 2012: Dynamics of carbon exchange in a Eucalyptus forest in response to interacting disturbance factors. *Agricultural and Forest Meteorolgy*, **153**, 67-81.

Ketola, T., V. Kellermann, T.N. Kristensen, and V. Loeschcke, 2012: Constant, cycling, hot and cold thermal environments: strong effects on mean viability but not on genetic estimates. *Journal of Evolutionary Biology*, **25(6)**, 1209-1215.

Kgope, B.S., W.J. Bond, and G.F. Midgley, 2010: Growth responses of African savanna trees implicate atmospheric CO_2 as a driver of past and current changes in savanna tree cover. *Austral Ecology*, **35(4)**, 451-463.

Kharuk, V.I., K.J. Ranson, P.A. Oskorbin, S.T. Im, and M.L. Dvinskaya, 2013: Climate induced birch mortality in Trans-Baikal lake region, Siberia. *Forest Ecology and Management*, **289**, 385-392.

Kherchouche, D., M. Kalla, E.M. Gutiérrez, S. Attalah, and M. Bouzghaia, 2012: Impact of droughts on *Cedrus atlantica* forests dieback in the Aurès (Algeria). *Journal of Life Sciences*, **6**, 1262-1269.

Khoury, C., B. Laliberte, and L. Guarino, 2010: Trends in *ex situ* conservation of plant genetic resources: a review of global crop and regional conservation strategies. *Genetic Resources and Crop Evolution*, **57(4)**, 625-639.

Kiesecker, J.M., 2011: Global stressors and the global decline of amphibians: tipping the stress immunocompetency axis. *Ecological Research*, **26(5)**, 897-908.

Kimball, S., A.L. Angert, T.E. Huxman, and D.L. Venable, 2010: Contemporary climate change in the Sonoran Desert favors cold-adapted species. *Global Change Biology*, **16(5)**, 1555-1565.

Kindermann, G.E., I. McCallum, S. Fritz, and M. Obersteiner, 2008: A global forest growing stock, biomass and carbon map based on FAO statistics. *Silva Fennica*, **42(3)**, 387-396.

Kinlan, B.P. and S.D. Gaines, 2003: Propagule dispersal in marine and terrestrial environments: a community perspective. *Ecology*, **84(8)**, 2007-2020.

Kint, V., W. Aertsen, M. Campioli, D. Vansteenkiste, A. Delcloo, and B. Muys, 2012: Radial growth change of temperate tree species in response to altered regional climate and air quality in the period 1901-2008. *Climatic Change*, **115(2)**, 343-363.

Kirdyanov, A.V., F. Hagedorn, A.A. Knorre, E.V. Fedotova, E.A. Vaganov, M.M. Naurzbaev, P.A. Moiseev, and A. Rigling, 2012: 20th century tree-line advance and vegetation changes along an altitudinal transect in the Putorana Mountains, northern Siberia. *Boreas*, **41(1)**, 56-67.

Kirilenko, A.P. and R.A. Sedjo, 2007: Climate change impacts on forestry. *Proceedings of the National Academy of Sciences of the United States of America*, **104(50)**, 19697-19702.

Kirschbaum, M.U.F., S. Saggar, K.R. Tate, D.L. Giltrap, A.-G.E. Ausseil, S. Greenhalgh, and D. Whitehead, 2012: Comprehensive evaluation of the climate-change implications of shifting land use between forest and grassland: New Zealand as a case study. *Agriculture, Ecosystems & Environment*, **150**, 123-138.

Kirwan, M.L. and L.K. Blum, 2011: Enhanced decomposition offsets enhanced productivity and soil carbon accumulation in coastal wetlands responding to climate change. *Biogeosciences*, **8(4)**, 987-993.

Kjøhl, M., A. Nielsen, and N.C. Stenseth, 2011: *Potential Effects of Climate Change on Crop Pollination.* Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 38 pp.

Klanderud, K. and O. Totland, 2005: Simulated climate change altered dominance hierarchies and diversity of an alpine biodiversity hotspot. *Ecology*, **86(8)**, 2047-2054.

Klausmeyer, K.R. and M.R. Shaw, 2009: Climate change, habitat loss, protected areas and the climate adaptation potential of species in Mediterranean ecosystems worldwide. *PLoS One*, **4(7)**, e6392, doi:10.1371/journal.pone.0006392.

Klein Goldewijk, K., A. Beusen, and P. Janssen, 2010: Long term dynamic modeling of global population and built-up area in a spatially explicit way: HYDE 3.1. *The Holocene*, **20(4)**, 565-573.

Klein Goldewijk, K., A. Beusen, G. van Drecht, and M. de Vos, 2011: The HYDE 3.1 spatially explicit database of human induced land use change over the past 12,000 years. *Global Ecology and Biogeography*, **20**, 73-86.

Klingberg, J., M. Engardt, J. Uddling, P.E. Karlsson, and H. Pleijel, 2011: Ozone risk for vegetation in the future climate of Europe based on stomatal ozone uptake calculations. *Tellus Series A: Dynamic Meteorology and Oceanography*, **63(1)**, 174-187.

Klos, R.J., G.G. Wang, W.L. Bauerle, and J.R. Rieck, 2009: Drought impact on forest growth and mortality in the southeast USA: an analysis using Forest Health and Monitoring data. *Ecological Applications*, **19(3)**, 699-708.

Knapp, A.K., J.M. Briggs, S.L. Collins, S.R. Archer, M.S. Bret-Harte, B.E. Ewers, and D.P. Peters, 2007: Shrub encroachment in North American grasslands: shifts in growth form dominance rapidly alters control of ecosystem carbon inputs. *Global Change Biology*, **14(3)**, 615-623.

Knapp, A.K., C. Beier, D.D. Briske, A.T. Classen, Y. Luo, M. Reichstein, M.D. Smith, S.D. Smith, J.E. Bell, P.A. Fay, J.L. Heisler, S.W. Leavitt, R. Sherry, B. Smith, and E. Weng, 2008: Consequences of more extreme precipitation regimes for terrestrial ecosystems. *Bioscience*, **58(9)**, 811-821.

Knapp, S., I. Kühn, R. Wittig, W.A. Ozinga, P. Poschlod, and S. Klotz, 2008: Urbanization causes shifts in species' trait state frequencies. *Preslia*, **80(4)**, 375-388.

Knapp, S., L. Dinsmore, C. Fissore, S.E. Hobbie, I. Jakobsdottir, J. Kattge, J.R. King, S. Klotz, J.P. McFadden, and J.M. Cavender-Bares, 2012: Phylogenetic and functional characteristics of household yard floras and their changes along an urbanization gradient. *Ecology*, **93(8 Suppl.)**, S83–S98.

Knohl, A. and D.D. Baldocchi, 2008: Effects of diffuse radiation on canopy gas exchange processes in a forest ecosystem. *Journal of Geophysical Research: Biogeosciences*, **113(G2)**, G02023, doi:10.1029/2007JG000663.

Knox, R., G. Bisht, J. Wang, and R. Bras, 2011: Precipitation variability over the forest-to-nonforest transition in southwestern Amazonia. *Journal of Climate*, **24**, 2368-2377.

Knudsen, E., A. Linden, C. Both, N. Jonzen, F. Pulido, N. Saino, W.J. Sutherland, L.A. Bach, T. Coppack, T. Ergon, P. Gienapp, J.A. Gill, O. Gordo, A. Hedenstroom, E. Lehikoinen, P.P. Marra, A.P. Moller, A.L.K. Nilsson, G. Peron, E. Ranta, D. Rubolini, T.H. Sparks, F. Spina, C.E. Studds, S.A. Saether, P. Tryjanowski, and N.C. Stenseth, 2011: Challenging claims in the study of migratory birds and climate change. *Biological Reviews*, **86(4)**, 928-946.

Knutti, R. and J. Sedláček, 2012: Robustness and uncertainties in the new CMIP5 climate model projections. *Nature Climate Change*, **3**, 369-373.

Koehler, I.H., P.R. Poulton, K. Auerswald, and H. Schnyder, 2010: Intrinsic water-use efficiency of temperate seminatural grassland has increased since 1857: an analysis of carbon isotope discrimination of herbage from the Park Grass Experiment. *Global Change Biology*, **16(5)**, 1531-1541.

Kollár, J., P. Hrubík, and S. Tkáčová, 2009: Monitoring of harmful insect species in urban conditions in selected model areas of Slovakia. *Plant Protection Science*, **45**, 119-124.

Kollberg, I., H. Bylund, A. Schmidt, J. Gershenzon, and C. Björkman, 2013: Multiple effects of temperature, photoperiod and food quality on the performance of a pine sawfly. *Ecological Entomology*, **38(2)**, 201-208.

Konarzewski, T.K., B.R. Murray, and R.C. Godfree, 2012: Rapid development of adaptive, climate-driven clinal variation in seed mass in the invasive annual forb *Echium plantagineum* L. *PLoS One*, **7(12)**, e49000, doi:10.1371/journal.pone.0049000.

Kongstad, J., I.K. Schmidt, T. Riis-Nielsen, M.F. Arndal, T.N. Mikkelsen, and C. Beier, 2012: High resilience in heathland plants to changes in temperature, drought, and CO_2 in combination: results from the CLIMAITE Experiment. *Ecosystems*, **15(2)**, 269-283.

Körner, C. and D. Basler, 2010: Phenology under global warming. *Science*, **327(5972)**, 1461-1462.

Körner, C., J.A. Morgan, and R. Norby, 2007: CO_2 fertilisation: when, where, how much? In: *Terrestrial Ecosystems in a Changing World* [Canadell, S.G., D.E. Pataki, and L.F. Pitelka (eds.)]. Springer, Berlin Heidelberg, Germany, pp. 9-22.

Koutavas, A., 2008: Late 20th century growth acceleration in greek firs (*Abies cephalonica*) from Cephalonia Island, Greece: a CO_2 fertilization effect? *Dendrochronologia*, **26(1)**, 13-19.

Kovach-Orr, C. and G.F. Fussmann, 2013: Evolutionary and plastic rescue in multitrophic model communities. *Philosophical Transactions of the Royal Society B*, **368(1610)**, 20120084, doi:10.1098/rstb.2012.0084.

Koven, C.D., W.J. Riley, and A. Stern, 2013: Analysis of permafrost thermal dynamics and response to climate change in the CMIP5 Earth System Models. *Journal of Climate*, **26(6)**, 1877-1900.

Kraft, N.J.B., M.R. Metz, R.S. Condit, and J. Chave, 2010: The relationship between wood density and mortality in a global tropical forest data set. *New Phytologist*, **188(4)**, 1124-1136.

Kramer, K., B. Degen, J. Buschbom, T. Hickler, W. Thuiller, M.T. Sykes, and W. de Winter, 2010: Modelling exploration of the future of European beech (*Fagus sylvatica* L.) under climate change – range, abundance, genetic diversity and adaptive response. *Forest Ecology and Management*, **259(11)**, 2213-2222.

Kramer, K., R.J. Bijlsma, T. Hickler, and W. Thuiller, 2012: Why would plant species become extinct locally if growing conditions improve? *International Journal of Biological Sciences*, **8(8)**, 1121-1129.

Kremer, A., O. Ronce, J.J. Robledo-Arnuncio, F. Guillaume, G. Bohrer, R. Nathan, J.R. Bridle, R. Gomulkiewicz, E.K. Klein, K. Ritland, A. Kuparinen, S. Gerber, and S. Schueler, 2012: Long-distance gene flow and adaptation of forest trees to rapid climate change. *Ecology Letters*, **15(4)**, 378-392.

Kriegler, E., J.W. Hall, H. Held, R. Dawson, and H.J. Schellnhuber, 2009: Imprecise probability assessment of tipping points in the climate system. *Proceedings of the National Academy of Sciences of the United States of America*, **106(13)**, 5041-5046.

Kropelin, S., D. Verschuren, A.M. Lezine, H. Eggermont, C. Cocquyt, P. Francus, J.P. Cazet, M. Fagot, B. Rumes, J.M. Russell, F. Darius, D.J. Conley, M. Schuster, H. von Suchodoletz, and D.R. Engstrom, 2008: Climate-driven ecosystem succession in the Sahara: the past 6000 years. *Science*, **320(5877)**, 765-768.

Kudo, G., Y. Amagai, B. Hoshino, and M. Kaneko, 2011: Invasion of dwarf bamboo into alpine snow-meadows in northern Japan: pattern of expansion and impact on species diversity. *Ecology and Evolution*, **1(1)**, 85-96.

Kuhlmann, M., D. Guo, R. Veldtman, and J. Donaldson, 2012: Consequences of warming up a hotspot: species range shifts within a centre of bee diversity. *Diversity and Distributions*, **18(9)**, 885-897.

Kukowski, K., S. Schwinning, and B. Schwartz, 2013: Hydraulic responses to extreme drought conditions in three co-dominant tree species in shallow soil over bedrock. *Oecologia*, **171(4)**, 819-830.

Kuldna, P., K. Peterson, H. Poltimae, and J. Luig, 2009: An application of DPSIR framework to identify issues of pollinator loss. *Ecological Economics*, **69(1)**, 32-42.

Kullman, L. and L. Öberg, 2009: Post-Little Ice Age tree line rise and climate warming in the Swedish Scandes: a landscape ecological perspective. *Journal of Ecology*, **97(3)**, 415-429.

Kundzewicz, Z.W., L.J. Mata, N.W. Arnell, P. Döll, P. Kabat, B. Jiménez, K.A. Miller, T. Oki, Z. Sen, and I.A. Shiklomanov, 2007: Freshwater resources and their management. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 173-210.

Kuparinen, A., O. Savolainen, and F.M. Schurr, 2010: Increased mortality can promote evolutionary adaptation of forest trees to climate change. *Forest Ecology and Management*, **259(5)**, 1003-1008.

Kurz, W.A., C.C. Dymond, G. Stinson, G.J. Rampley, E.T. Neilson, A.L. Carroll, T. Ebata, and L. Safranyik, 2008: Mountain pine beetle and forest carbon feedback to climate change. *Nature*, **452(7190)**, 987-990.

Kusano, T. and M. Inoue, 2008: Long-term trends toward earlier breeding of Japanese amphibians. *Journal of Herpetology*, **42(4)**, 608-614.

Kuussaari, M., R. Bommarco, R.K. Heikkinen, A. Helm, J. Krauss, R. Lindborg, E. Ockinger, M. Partel, J. Pino, F. Roda, C. Stefanescu, T. Teder, M. Zobel, and I. Steffan-Dewenter, 2009: Extinction debt: a challenge for biodiversity conservation. *Trends in Ecology & Evolution*, **24(10)**, 564-571.

Kvalevåg, M.M. and G. Myhre, 2007: Human impact on direct and diffuse solar radiation during the industrial era. *Journal of Climate*, **20(19)**, 4874-4883.

Lambert, A.M., A.J. Miller-Rushing, and D.W. Inouye, 2010: Changes in snowmelt date and summer precipitation affect the flowering phenology of *Erythronium grandiflorum* (Glacier Lily; Liliaceae). *American Journal of Botany*, **97(9)**, 1431-1437.

Lambin, E.F. and P. Meyfroidt, 2011: Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences of the United States of America*, **108(9)**, 3465-3472.

Lane, J.E., L.E.B. Kruuk, A. Charmantier, J.O. Murie, and F.S. Dobson, 2012: Delayed phenology and reduced fitness associated with climate change in a wild hibernator. *Nature*, **489(7417)**, 554-557.

Langan, S.J., L. Johnston, M.J. Donaghy, A.F. Youngson, D.W. Hay, and C. Soulsby, 2001: Variation in river water temperatures in an upland stream over a 30-year period. *Science of the Total Environment*, **265(1-3)**, 195-207.

Langley, J.A. and J.P. Megonigal, 2010: Ecosystem response to elevated CO_2 levels limited by nitrogen-induced plant species shift. *Nature*, **466(7302)**, 96-99.

Lantz, T.C., S.V. Kokelj, S.E. Gergel, and G.H.R. Henry, 2009: Relative impacts of disturbance and temperature: persistent changes in microenvironment and vegetation in retrogressive thaw slumps. *Global Change Biology*, **15(7)**, 1664-1675.

Lantz, T.C., S.E. Gergel, and G.H.R. Henry, 2010: Response of green alder (*Alnus viridis* subsp. *fruticosa*) patch dynamics and plant community composition to fire and regional temperature in north-western Canada. *Journal of Biogeography*, **37(8)**, 1597-1610.

Lapola, D.M., M.D. Oyama, and C.A. Nobre, 2009: Exploring the range of climate biome projections for tropical South America: the role of CO_2 fertilization and seasonality. *Global Biogeochemical Cycles*, **23(3)**, GB3003, doi:10.1029/2008GB003357.

Lapola, D.M., R. Schaldach, J. Alcamo, A. Bondeau, J. Koch, C. Koelking, and J.A. Priess, 2010: Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proceedings of the National Academy of Sciences of the United States of America*, **107(8)**, 3388-3393.

Larsen, K.S., L.C. Andresen, C. Beier, S. Jonasson, K.R. Albert, P. Ambus, M.F. Arndal, M.S. Carter, S. Christensen, M. Holmstrup, A. Ibrom, J. Kongstad, L. van der Linden, K. Maraldo, A. Michelsen, T.N. Mikkelsen, K. Pilegaard, A. Prieme, H. Ro-Poulsen, I.K. Schmidt, M.B. Selsted, and K. Stevnbak, 2011: Reduced N cycling in response to elevated CO_2, warming, and drought in a Danish heathland: synthesizing results of the CLIMAITE project after two years of treatments. *Global Change Biology*, **17(5)**, 1884-1899.

Laurance, W.F., D.C. Useche, L.P. Shoo, S.K. Herzog, M. Kessler, F. Escobar, G. Brehm, J.C. Axmacher, I.C. Chen, L.A. Gamez, P. Hietz, K. Fiedler, T. Pyrcz, J. Wolf, C.L. Merkord, C. Cardelus, A.R. Marshall, C. Ah-Peng, G.H. Aplet, M.D. Arizmendi, W.J. Baker, J. Barone, C.A. Bruhl, R.W. Bussmann, D. Cicuzza, G. Eilu, M.E. Favila, A. Hemp, C. Hemp, J. Homeier, J. Hurtado, J. Jankowski, G. Kattan, J. Kluge, T. Kromer, D.C. Lees, M. Lehnert, J.T. Longino, J. Lovett, P.H. Martin, B.D. Patterson, R.G. Pearson, K.S.H. Peh, B. Richardson, M. Richardson, M.J. Samways, F. Senbeta, T.B. Smith, T.M.A. Utteridge, J.E. Watkins, R. Wilson, S.E. Williams, and C.D. Thomas, 2011: Global warming, elevational ranges and the vulnerability of tropical biota. *Biological Conservation*, **144(1)**, 548-557.

Lavergne, S., N. Mouquet, W. Thuiller, and O. Ronce, 2010: Biodiversity and climate change: integrating evolutionary and ecological responses of species and communities. *Annual Review of Ecology, Evolution, and Systematics*, **41**, 321-350.

Lavergne, S., M.E.K. Evans, I.J. Burfield, F. Jiguet, and Thuiller.W., 2013: Are species' responses to global change predicted by past niche evolution? *Philosophical Transactions of the Royal Society B*, **368(1610)**, 20120091, doi:10.1098/rstb.2012.0091.

Lawrence, D.M. and S.C. Swenson, 2011: Permafrost response to increasing Arctic shrub abundance depends on the relative influence of shrubs on local soil cooling versus large-scale climate warming. *Environmental Research Letters*, **6(4)**, 045504, doi:10.1088/1748-9326/6/4/045504.

Lawrence, D.M., P.E. Thornton, K.W. Oleson, and G.B. Bonan, 2007: The partitioning of evpotranspiration into transpiration, soil evaporation, and canopy evaporation in a GCM: impacts on land-atmosphere interaction. *Journal of Hydrometeorology*, **8**, 862-880.

Lawson, C.R., J.J. Bennie, C.D. Thomas, J.A. Hodgson, and R.J. Wilson, 2012: Local and landscape management of an expanding range margin under climate change. *Journal of Applied Ecology*, **49**, 552-561.

Le Conte, Y. and M. Navajas, 2008: Climate change: impact on honey bee populations and diseases. *Revue Scientifique Et Technique – Office International Des Epizooties*, **27(2)**, 499-510.

Le Quéré, C., M.R. Raupach, J.G. Canadell, and G. Marland, 2009: Trends in the sources and sinks of carbon dioxide. *Nature Geoscience*, **2(12)**, 831-836.

Le Quéré, C., R.J. Andres, T. Boden, T. Conway, R.A. Houghton, J.I. House, G. Marland, G.P. Peters, G. van der Werf, A. Ahlström, R.M. Andrew, L. Bopp, J.G. Canadell, P. Ciais, S.C. Doney, C. Enright, P. Friedlingstein, C. Huntingford, A.K. Jain, C. Jourdain, E. Kato, R.F. Keeling, K. Klein Goldewijk, S. Levis, P. Levy, M. Lomas, B. Poulter, M.R. Raupach, J. Schwinger, S. Sitch, B.D. Stocker, N. Viovy, S. Zaehle, and N. Zeng, 2012: The global carbon budget 1959-2011. *Earth System Science Data*, **5(2)**, 1107-1157.

Leadley, P., H.N. Pereira, R. Alkemade, J.F. Fernandez-Manjarrés, V. Proença, J.P.W. Scharlemann, and M.J. Walpole, 2010: *Biodiversity Scenarios: Projections of 21st Century Change in Biodiversity and Associated Ecosystem Services.* A Technical Report for the Global Biodiversity Outlook 3, Technical Series No. 50, Secretariat of the Convention on Biological Diversity, Montreal, Canada, 132 pp.

Leakey, A.D.B., E.A. Ainsworth, C.J. Bernacchi, A. Rogers, S.P. Long, and D.R. Ort, 2009: Elevated CO_2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *Journal of Experimental Botany*, **60(10)**, 2859-2876.

Leal, M. and A.R. Gunderson, 2012: Rapid change in the thermal tolerance of a tropical lizard. *American Naturalist*, **180(6)**, 815-822.

Ledger, M.E., L.E. Brown, F.K. Edwards, A.M. Milner, and G. Woodward, 2013: Drought alters the structure and functioning of complex food webs. *Nature Climate Change*, **3(3)**, 223-227.

Lee, M., P. Manning, J. Rist, S.A. Power, and C. Marsh, 2010: A global comparison of grassland biomass responses to CO_2 and nitrogen enrichment. *Philosophical Transactions of the Royal Society B*, **365(1549)**, 2047-2056.

Leishman, M.R., T. Haslehurst, A. Ares, and Z. Baruch, 2007: Leaf trait relationships of native and invasive plants: community- and global-scale comparisons. *New Phytologist*, **176(3)**, 635-643.

Lenihan, J.M., D. Bachelet, R.P. Neilson, and R. Drapek, 2008: Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California. *Climatic Change*, **87**, S215-S230.

Lenoir, J., J.C. Gegout, P.A. Marquet, P. de Ruffray, and H. Brisse, 2008: A significant upward shift in plant species optimum elevation during the 20th century. *Science*, **320(5884)**, 1768-1771.

Lenoir, J., J.C. Gegout, J.L. Dupouey, D. Bert, and J.C. Svenning, 2010: Forest plant community changes during 1989-2007 in response to climate warming in the Jura Mountains (France and Switzerland). *Journal of Vegetation Science*, **21(5)**, 949-964.

Lenton, T.M., H. Held, E. Kriegler, J.W. Hall, W. Lucht, S. Rahmstorf, and H.J. Schellnhuber, 2008: Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences of the United States of America*, **105(6)**, 1786-1793.

Leonelli, G., M. Pelfini, U. Morra di Cella, and V. Garavaglia, 2011: Climate warming and the recent treeline shift in the European Alps: the role of geomorphological factors in high-altitude sites. *AMBIO: A Journal of the Human Environment*, **40(3)**, 264-273.

Lermen, D., B. Blomeke, R. Browne, A. Clarke, P.W. Dyce, T. Fixemer, G.R. Fuhr, W.V. Holt, K. Jewgenow, R.E. Lloyd, S. Lotters, M. Paulus, G.M. Reid, D.H. Rapoport, D. Rawson, J. Ringleb, O.A. Ryder, G. Sporl, T. Schmitt, M. Veith, and P. Muller, 2009: Cryobanking of viable biomaterials: implementation of new strategies for conservation purposes. *Molecular Ecology*, **18(6)**, 1030-1033.

Leuning, R., 1995: A critical appraisal of a combined stomatalphotosynthesis model for C_3 plants. *Plant, Cell and Environment*, **18**, 339-355.

Leuzinger, S. and C. Körner, 2010: Rainfall distribution is the main driver of runoff under future CO_2-concentration in a temperate deciduous forest. *Global Change Biology*, **16(1)**, 246-254.

Leuzinger, S., Y.Q. Luo, C. Beier, W. Dieleman, S. Vicca, and C. Korner, 2011: Do global change experiments overestimate impacts on terrestrial ecosystems? *Trends in Ecology & Evolution*, **26(5)**, 236-241.

Levis, S., 2010: Modeling vegetation and land use in models of the Earth System. *Wiley Interdisciplinary Reviews: Climate Change*, **1(6)**, 840-856.

Lewis, S.L., J. Lloyd, S. Sitch, E.T.A. Mitchard, and W.F. Laurance, 2009a: Changing ecology of tropical forests: evidence and drivers. *Annual Review of Ecology Evolution and Systematics*, **40**, 529-549.

Lewis, S.L., G. Lopez-Gonzalez, B. Sonke, K. Affum-Baffoe, T.R. Baker, L.O. Ojo, O.L. Phillips, J.M. Reitsma, L. White, J.A. Comiskey, M.N. Djuikouo, C.E.N. Ewango, T.R. Feldpausch, A.C. Hamilton, M. Gloor, T. Hart, A. Hladik, J. Lloyd, J.C. Lovett, J.R. Makana, Y. Malhi, F.M. Mbago, H.J. Ndangalasi, J. Peacock, K.S.H. Peh, D. Sheil, T. Sunderland, M.D. Swaine, J. Taplin, D. Taylor, S.C. Thomas, R. Votere, and H. Wöll, 2009b: Increasing carbon storage in intact African tropical forests. *Nature*, **457**, 1003-1007.

Lewis, S.L., P.M. Brando, O.L. Phillips, G.M.F. van der Heijden, and D. Nepstad, 2011: The 2010 Amazon drought. *Science*, **331(6017)**, 554.

Li, D.Z. and H.W. Pritchard, 2009: The science and economics of *ex situ* plant conservation. *Trends in Plant Science*, **14(11)**, 614-621.

Li, W.H., R.E. Dickinson, R. Fu, G.Y. Niu, Z.L. Yang, and J.G. Canadell, 2007: Future precipitation changes and their implications for tropical peatlands. *Geophysical Research Letters*, **34**, L01403, doi:10.1029/2006GL028364.

Li, Z., W.-z. Liu, X.-c. Zhang, and F.-l. Zheng, 2009: Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. *Journal of Hydrology*, **377(1-2)**, 35-42.

Liao, J.D., T.W. Boutton, and J.D. Jastrow, 2006: Storage and dynamics of carbon and nitrogen in soil physical fractions following woody plant invasion of grassland. *Soil Biology and Biochemistry*, **38(11)**, 3184-3196.

Liljedahl, A., L. Hinzman, R. Busey, and K. Yoshikawa, 2007: Physical short-term changes after a tussock tundra fire, Seward Peninsula, Alaska. *Journal of Geophysical Research: Earth Surface*, **112(F2)**, F02S07, doi:10.1029/2006JF000554.

Limpens, J., F. Berendse, C. Blodau, J.G. Canadell, C. Freeman, J. Holden, N. Roulet, H. Rydin, and G. Schaepman-Strub, 2008: Peatlands and the carbon cycle: from local processes to global implications – a synthesis. *Biogeosciences*, **5(5)**, 1475-1491.

Limpens, J., G. Granath, U. Gunnarsson, R. Aerts, S. Bayley, L. Bragazza, J. Bubier, A. Buttler, L.J.L. van den Berg, A.J. Francez, R. Gerdol, P. Grosvernier, M. Heijmans, M.R. Hoosbeek, S. Hotes, M. Ilomets, I. Leith, E.A.D. Mitchell, T. Moore, M.B. Nilsson, J.F. Nordbakken, L. Rochefort, H. Rydin, L.J. Sheppard, M. Thormann, M.M. Wiedermann, B.L. Williams, and B. Xu, 2011: Climatic modifiers of the response to nitrogen deposition in peat-forming Sphagnum mosses: a meta-analysis. *New Phytologist*, **191(2)**, 496-507.

Linares, J.C., J.J. Camarero, and J.A. Carreira, 2009: Interacting effects of changes in climate and forest cover on mortality and growth of the southernmost European fir forests. *Global Ecology and Biogeography*, **18(4)**, 485-497.

Linares, J.C, P.A. Tíscar, J.J. Camarero, L. Taïqui, and B. Viñegla, 2011: Tree growth decline on relict western-Mediterrenean mountain forests: causes and impacts. In: *Forest Decline: Causes and Impacts* [Jenkins, J.A.(ed)]. Nova Publishers, New York, NY, USA, pp. 91-110.

Lindner, M., M. Maroschek, S. Netherer, A. Kremer, A. Barbati, J. Garcia-Gonzalo, R. Seidl, S. Delzon, P. Corona, M. Kolstrom, M.J. Lexer, and M. Marchetti, 2010: Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management*, **259(4)**, 698-709.

Lindroth, R.L., 2010: Impacts of elevated atmospheric CO_2 and O_3 on forests: phytochemistry, trophic interactions, and ecosystem dynamics. *Journal of Chemical Ecology*, **36(1)**, 2-21.

Lips, K.R., J. Diffendorfer, J.R. Mendelson, and M.W. Sears, 2008: Riding the wave: reconciling the roles of disease and climate change in amphibian declines. *PLoS Biology*, **6(3)**, 441-454.

Littell, J.S., D. McKenzie, D.L. Peterson, and A.L. Westerling, 2009: Climate and wildfire area burned in western U.S. ecoprovinces, 1916-2003. *Ecological Applications*, **19**, 1003-1021.

Littell, J.S., E.E. Oneil, D. McKenzie, J.A. Hicke, J.A. Lutz, R.A. Norheim, and M.M. Elsner, 2010: Forest ecosystems, disturbance, and climatic change in Washington State, USA. *Climatic Change*, **102(1-2)**, 129-158.

Liu, H., A. Park Williams, C. Allen, D. Guo, X. Wu, O.A. Anenkhonov, E. Liang, D.V. Sandanov, Y. Yin, Z. Qi, and N.K. Badmaeva, 2013: Rapid warming accelerates tree growth decline in semi-arid forests of Inner Asia. *Global Change Biology*, **19(8)**, 2500-2510.

Liu, W., Z. Zhang, and S. Wan, 2009: Predominant role of water in regulating soil and microbial respiration and their responses to climate change in a semiarid grassland. *Global Change Biology*, **15(1)**, 184-195.

Livingstone, D.M. and R. Adrian, 2009: Modeling the duration of intermittent ice cover on a lake for climate-change studies. *Limnology and Oceanography*, **54(5)**, 1709-1722.

Lloyd, A.H. and C.L. Fastie, 2003: Recent changes in tree line forest distribution and structure in interior Alaska. *Ecoscience*, **10**, 176-185.

Lloyd, A.H., A.G. Bunn, and L. Berner, 2011: A latitudinal gradient in tree growth response to climate warming in the Siberian taiga. *Global Change Biology*, **17(5)**, 1935-1945.

Lloyd, J. and G.D. Farquhar, 2008: Effects of rising temperatures and CO_2 on the physiology of tropical forest trees. *Philosophical Transactions of the Royal Society B*, **363(1498)**, 1811-1817.

Loader, N.J., R.P.D. Walsh, I. Robertson, K. Bidin, R.C. Ong, G. Reynolds, D. McCarroll, M. Gagen, and G.H.F. Young, 2011: Recent trends in the intrinsic water-use efficiency of ringless rainforest trees in Borneo. *Philosophical Transactions of the Royal Society B*, **366(1582)**, 3330-3339.

Loarie, S.R., P.B. Duffy, H. Hamilton, G.P. Asner, C.B. Field, and D.D. Ackerly, 2009: The velocity of climate change. *Nature*, **462**, 1052-1055.

Loarie, S.R., D.B. Lobell, G.P. Asner, Q. Mu, and C.B. Field, 2011: Direct impacts on local climate of sugar-cane expansion in Brazil. *Nature Climate Change*, **1(2)**, 105-109.

Lobell, D.B., W. Schlenker, and J. Costa-Roberts, 2011: Climate trends and global crop production since 1980. *Science*, **333(6042)**, 616-620.

Long, S.P., E.A. Ainsworth, A. Rogers, and D.R. Ort, 2004: Rising atmospheric carbon dioxied: plants FACE the future. *Annual Review of Plant Biology*, **55(1)**, 591-628.

Longobardi, P., A. Montenegro, H. Beltrami, and M. Eby, 2012: Spatial scale dependency of the modelled climatic response to deforestation. *Biogeosciences Discussions*, **9**, 14639-14687.

Lopez-Vaamonde, C., D. Agassiz, S. Augustin, J. De Prins, W. De Prins, S. Gomboc, P. Ivinskis, O. Karsholt, A. Koutroumpas, F. Koutroumpa, Z. Laštůvka, E. Marabuto, E. Olivella, L. Przybylowicz, A. Roques, N. Ryrholm, H. Šefrová, P. Šima, I. Sims, S. Sinev, B. Skulev, R. Tomov, A. Zilli, and D. Lees, 2010: Lepidoptera. In: *Biorisk, Vol. 4, Part 2: Alien Terrestrial Arthropods of Europe* [Roques, A., M. Kenis, D. Lees, C. Lopez-Vaamonde, W. Rabitsch, J.-Y. Rasplus, and D.B. Roy (eds.)]. Pensoft Publishers, Sofia, Bulgaria, pp. 603-668.

Loreau, M., N. Mouquet, and R.D. Holt, 2003: Meta-ecosystems: a theoretical framework for a spatial ecosystem ecology. *Ecology Letters*, **6(8)**, 673-679.

Lorenzen, E.D., D. Nogues-Bravo, L. Orlando, J. Weinstock, J. Binladen, K.A. Marske, A. Ugan, M.K. Borregaard, M.T.P. Gilbert, R. Nielsen, S.Y.W. Ho, T. Goebel, K.E. Graf, D. Byers, J.T. Stenderup, M. Rasmussen, P.F. Campos, J.A. Leonard, K.P. Koepfli, D. Froese, G. Zazula, T.W. Stafford, K. Aaris-Sorensen, P. Batra, A.M. Haywood, J.S. Singarayer, P.J. Valdes, G. Boeskorov, J.A. Burns, S.P. Davydov, J. Haile, D.L. Jenkins, P. Kosintsev, T. Kuznetsova, X.L. Lai, L.D. Martin, H.G. McDonald, D. Mol, M. Meldgaard, K. Munch, E. Stephan, M. Sablin, R.S. Sommer, T. Sipko, E. Scott, M.A. Suchard, A. Tikhonov, R. Willerslev, R.K. Wayne, A. Cooper, M. Hofreiter, A. Sher, B. Shapiro, C. Rahbek, and E. Willerslev, 2011: Species-specific responses of Late Quaternary megafauna to climate and humans. *Nature*, **479**, 359-364.

Loss, S.R., L.A. Terwilliger, and A.C. Peterson, 2011: Assisted colonization: integrating conservation strategies in the face of climate change. *Biological Conservation*, **144(1)**, 92-100.

Loustau, D., 2010: *Forests*, *Carbon Cycle and Climate Change*. Éditions Quae, Versailles, France, 350 pp.

Lu, C.Q., H.Q. Tian, M.L. Liu, W. Ren, X.F. Xu, G.S. Chen, and C. Zhang, 2012: Effect of nitrogen deposition on China's terrestrial carbon uptake in the context of multifactor environmental changes. *Ecological Applications*, **22(1)**, 53-75.

Lu, J., C. Deser, and T. Reichler, 2009: Cause of the widening of the tropical belt since 1958. *Geophysical Research Letters*, **36**, L03803, doi:10.1029/2008GL036076.

Luckman, B. and T. Kavanagh, 2000: Impact of climate fluctuations on mountain environments in the Canadian Rockies. *AMBIO: A Journal of the Human Environment*, **29(7)**, 371-380.

Lunt, I.D., L.M. Winsemius, S.P. McDonald, J.W. Morgan, and R.L. Dehaan, 2010: How widespread is woody plant encroachment in temperate Australia? Changes in woody vegetation cover in lowland woodland and coastal ecosystems in Victoria from 1989 to 2005. *Journal of Biogeography*, **37(4)**, 722-732.

Luo, Y.Q., 2007: Terrestrial carbon-cycle feedback to climate warming. *Annual Review of Ecology Evolution and Systematics*, **38**, 683-712.

Luo, Y.Q., D. Gerten, G. Le Maire, W.J. Parton, E.S. Weng, X.H. Zhou, C. Keough, C. Beier, P. Ciais, W. Cramer, J.S. Dukes, B. Emmett, P.J. Hanson, A. Knapp, S. Linder, D. Nepstad, and L. Rustad, 2008: Modeled interactive effects of precipitation, temperature, and CO_2 on ecosystem carbon and water dynamics in different climatic zones. *Global Change Biology*, **14(9)**, 1986-1999.

Luyssaert, S., P. Ciais, S.L. Piao, E.D. Schulze, M. Jung, S. Zaehle, M.J. Schelhaas, M. Reichstein, G. Churkina, D. Papale, G. Abril, C. Beer, J. Grace, D. Loustau, G. Matteucci, F. Marnani, G.J. Nabuurs, H. Verbeeck, M. Sulkava, G.R. Van Der Werf, I.A. Janssens, and Members of the CarboEurope-IP Synthesis Team, 2010: The European carbon balance. 3: forests. *Global Change Biology*, **16(5)**, 1429-1450.

Lydeard, C., R.H. Cowie, W.F. Ponder, A.E. Bogan, P. Bouchet, S.A. Clark, K.S. Cummings, T.J. Frest, O. Gargominy, D.G. Herbert, R. Hershler, K.E. Perez, B. Roth, M. Seddon, E.E. Strong, and F.G. Thompson, 2004: The global decline of non-marine mollusks. *BioScience*, **54(4)**, 321-330.

Ma, L.N., X.T. Lu, Y. Liu, J.X. Guo, N.Y. Zhang, J.Q. Yang, and R.Z. Wang, 2011: The effects of warming and nitrogen addition on soil nitrogen cycling in a temperate grassland, Northeastern China. *PLoS One*, **6(11)**, e27645, doi:10.1371/journal.pone.0027645.

Ma, T. and C.G. Zhou, 2012: Climate-associated changes in spring plant phenology in China. *International Journal of Biometeorology*, **56(2)**, 269-275.

Ma, Z., C. Peng, Q. Zhu, H. Chen, G. Yu, W.H. Li, X. Zhou, W. Wang, and W. Zhang, 2012: Regional drought-induced reduction in the biomass carbon sink of Canada's boreal forests. *Proceedings of the National Academy of Sciences of the United States of America*, **109(7)**, 2423-2427.

MacDonald, G.M., 2010: Global warming and the Arctic: a new world beyond the reach of the Grinnellian niche? *The Journal of Experimental Biology*, **213**, 855-861.

MacDonald, G.M., K.D. Bennett, S.T. Jackson, L. Parducci, F.A. Smith, J.P. Smol, and K.J. Willis, 2008: Impacts of climate change on species, populations and communities: palaeobiogeographical insights and frontiers. *Progress in Physical Geography*, **32(2)**, 139-172.

Macedo, M.N., R.S. DeFries, D.C. Morton, C.M. Stickler, G.L. Galford, and Y.E. Shimabukuro, 2012: Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. *Proceedings of the National Academy of Sciences of the United States of America*, **109(4)**, 1341-1346.

Macias Fauria, M. and E.A. Johnson, 2008: Climate and wildfires in the North American boreal forest. *Philosophical Transactions of the Royal Society B*, **363(1501)**, 2317-2329.

Mack, M.C., K.K. Treseder, K.L. Manies, J.W. Harden, E.A.G. Schuur, J.G. Vogel, J.T. Randerson, and F.S. Chapin, 2008: Recovery of aboveground plant biomass and productivity after fire in mesic and dry black spruce forests of interior Alaska. *Ecosystems*, **11(2)**, 209-225.

Mack, M.C., M.S. Bret-Harte, T.N. Hollingsworth, R.R. Jandt, E.A.G. Schuur, G.R. Shaver, and D.L. Verbyla, 2011: Carbon loss from an unprecedented Arctic tundra wildfire. *Nature*, **475(7357)**, 489-492.

Mackelprang, R., M.P. Waldrop, K.M. DeAngelis, M.M. David, K.L. Chavarria, S.J. Blazewicz, E.M. Rubin, and J.K. Jansson, 2011: Metagenomic analysis of a permafrost microbial community reveals a rapid response to thaw. *Nature*, **480(7377)**, 368-371.

Maclachlan, J.S., J.J. Hellmann, and M.W. Schwarz, 2007: A framework for debate of assisted migration in an era of climate change. *Conservation Biology*, **21(2)**, 297-302.

Magalhães, M.F., P. Beja, I.J. Schlosser, and M.J. Collares-Pereira, 2007: Effects of multi-year droughts on fish assemblages of seasonally drying Mediterranean streams. *Freshwater Biology*, **52(8)**, 1494-1510.

Magnani, F., M. Mencuccini, M. Borghetti, P. Berbigier, F. Berninger, S. Delzon, A. Grelle, P. Hari, P.G. Jarvis, P. Kolari, A.S. Kowalski, H. Lankreijer, B.E. Law, A. Lindroth, D. Loustau, G. Manca, J.B. Moncrieff, M. Rayment, V. Tedeschi, R. Valentini, and J. Grace, 2007: The human footprint in the carbon cycle of temperate and boreal forests. *Nature*, **447(7146)**, 848-850.

Mainka, S.A. and G.W. Howard, 2010: Climate change and invasive species: double jeopardy. *Integrative Zoology*, **5(2)**, 102-111.

Maiorano, L., A. Falcucci, N.E. Zimmermann, A. Psomas, J. Pottier, D. Baisero, C. Rondinini, A. Guisan, and L. Boitani, 2011: The future of terrestrial mammals in the Mediterranean basin under climate change. *Philosophical Transactions of the Royal Society B*, **366(1578)**, 2681-2692.

Malcolm, J.R., C.R. Liu, R.P. Neilson, L. Hansen, and L. Hannah, 2006: Global warming and extinctions of endemic species from biodiversity hotspots. *Conservation Biology*, **20(2)**, 538-548.

Malhi, Y., J.T. Roberts, R.A. Betts, T.J. Killeen, W. Li, and C.A. Nobre, 2008: Climate change, deforestation, and the fate of the Amazon. *Science*, **319(5860)**, 169-172.

Malhi, Y., L.E.O.C. Aragao, D. Galbraith, C. Huntingford, R. Fisher, P. Zelazowski, S. Sitch, C. McSweeney, and P. Meir, 2009a: Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences of the United States of America*, **106(49)**, 20610-20615.

Malhi, Y., L. Aragao, D.B. Metcalfe, R. Paiva, C.A. Quesada, S. Almeida, L. Anderson, P. Brando, J.Q. Chambers, A.C.L. da Costa, L.R. Hutyra, P. Oliveira, S. Patino, E.H. Pyle, A.L. Robertson, and L.M. Teixeira, 2009b: Comprehensive assessment of carbon productivity, allocation and storage in three Amazonian forests. *Global Change Biology*, **15(5)**, 1255-1274.

Malmqvist, B., S.D. Rundle, A.P. Covich, A.G. Hildrew, C.T. Robinson, and C.R. Townsend, 2008: Prospects for streams and rivers: an ecological perspective. In: *Aquatic Ecosystems: Trends and Global Prospects* [Polunin, N.V.C. (ed.)]. Cambridge University Press, Cambridge, UK, pp. 19-29.

Maniatis, D., Y. Malhi, L.S. Andre, D. Mollicone, N. Barbier, S. Saatchi, M. Henry, L. Tellier, M. Schwartzenberg, and M. White, 2011: Evaluating the potential of commercial forest inventory data to report on forest carbon stock and forest carbon stock changes for REDD+ under the UNFCCC. *International Journal of Forestry Research*, **2011**, 134526, doi:10.1155/2011/134526.

Mann, D.H., T.S. Rupp, M.A. Olson, and P.A. Duffy, 2012: Is Alaska's boreal forest now crossing a major ecological threshold? *Arctic Antarctic and Alpine Research*, **44(3)**, 319-331.

Maraldo, K., I.K. Schmidt, C. Beier, and M. Holmstrup, 2008: Can field populations of the enchytraeid, *Cognettia sphagnetorum*, adapt to increased drought stress? *Soil Biology & Biochemistry*, **40(7)**, 1765-1771.

Marengo, J.A., J. Tomasella, L.M. Alves, W.R. Soares, and D.A. Rodriguez, 2011: The drought of 2010 in the context of historical droughts in the Amazon region. *Geophysical Research Letters*, **38(12)**, L12703, doi:10.1029/2011GL047436.

Marini, L., M. Ayres, A. Battisti, and M. Faccoli, 2012: Climate affects severity and altitudinal distribution of outbreaks in an eruptive bark beetle. *Climatic Change*, **115(2)**, 327-341.

Markovic, D., U. Scharfenberger, S. Schmutz, F. Pletterbauer, and C. Wolter, 2013: Variability and alterations of water temperatures across the Elbe and Danube River Basins. *Climatic Change*, **119(2)**, 375-389.

Marlon, J.R., P.J. Bartlein, M.K. Walsh, S.P. Harrison, K.J. Brown, M.E. Edwards, P.E. Higuera, M.J. Power, R.S. Anderson, C. Briles, A. Brunelle, C. Carcaillet, M. Daniels, F.S. Hu, M. Lavoie, C. Long, T. Minckley, P.J.H. Richard, A.C. Scott, D.S. Shafer, W. Tinner, C.E. Umbanhowar, and C. Whitlock, 2009: Wildfire responses to abrupt climate change in North America. *Proceedings of the National Academy of Sciences of the United States of America*, **106(8)**, 2519-2524.

Marlon, J.R., P.J. Bartlein, A.-L. Daniau, S.P. Harrison, S.Y. Maezumi, M.J. Power, W. Tinner, and B. Vanniére, 2013: Global biomass burning: a synthesis and review of Holocene paleofire records and their controls. *Quaternary Science Reviews*, **65**, 5-25.

Martí-Roura, M., P. Casals, and J. Romanyà, 2011: Temporal changes in soil organic C under Mediterranean shrublands and grasslands: impact of fire and drought. *Plant and Soil*, **338(1-2)**, 289-300.

Martin, D., T. Lal, C.B. Sachdev, and J.P. Sharma, 2010: Soil organic carbon storage changes with climate change, landform and land use conditions in Garhwal hills of the Indian Himalayan mountains. *Agriculture, Ecosystems & Environment*, **138(1-2)**, 64-73.

Martin, T.E. and J.L. Maron, 2012: Climate impacts on bird and plant communities from altered animal-plant interactions. *Nature Climate Change*, **2(3)**, 195-200.

Martinez-Alier, J., 2011: The EROI of Agriculture and its use by the Via Campesina. *The Journal of Peasant Studies*, **38(1)**, 145-160.

Martinez, P.J., 2012: Invasive crayfish in a high desert river: implications of concurrent invaders and climate change. *Aquatic Invasions*, **7(2)**, 219-234.

Maseyk, K., D. Hemming, A. Angert, S.W. Leavitt, and D. Yakir, 2011: Increase in water-use efficiency and underlying processes in pine forests across a precipitation gradient in the dry Mediterranean region over the past 30 years. *Oecologia*, **167(2)**, 573-585.

Maslin, M., M. Owen, R. Betts, S. Day, T. Dunkley Jones, and A. Ridgwell, 2010: Gas hydrates: past and future geohazard? *Philosophical Transactions of the Royal Society A*, **368(1919)**, 2369-2393.

Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Frame, H. Held, E. Kriegler, K.J. Mach, P.R. Matschoss, G.-K. Plattner, G.W. Yohe, and F.W. Zwiers, 2010: *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties.* Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, 5 pp., www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf.

Matthews, S.N., L.R. Iverson, A.M. Prasad, M.P. Peters, and P.G. Rodewald, 2011: Modifying climate change habitat models using tree species-specific assessments of model uncertainty and life history-factors. *Forest Ecology and Management*, **262(8)**, 1460-1472.

Matthiessen, B., E. Mielke, and U. Sommer, 2010: Dispersal decreases diversity in heterogeneous metacommunities by enhancing regional competition. *Ecology*, **91(7)**, 2022-2033.

Mattila, N., V. Kaitala, A. Komonen, J. Paivinen, and J.S. Kotiaho, 2011: Ecological correlates of distribution change and range shift in butterflies. *Insect Conservation and Diversity*, **4(4)**, 239-246.

Matusick, G., K.X. Ruthrof, and G.S.J. Hardy, 2012: Drought and heat triggers sudden and severe dieback in a dominant Mediterranean-type woodland species. *Open Journal of Forestry*, **2(4)**, 183-186.

Matusick, G., K.X. Ruthrof, N.C. Brouwers, B. Dell, and G.S.J. Hardy, 2013: Sudden forest canopy collapse corresponding with extreme drought and heat in a Mediterranean-type eucalypt forest in southwestern Australia. *European Journal of Forest Research*, **132(3)**, 497-510.

Matzek, V., 2012: Trait values, not trait plasticity, best explain invasive species' performance in a changing environment. *PLoS One*, **7(10)**, e48821, doi:10.1371/journal.pone.0048821.

Mayle, F.E. and M.J. Power, 2008: Impact of a drier Early-Mid-Holocene climate upon Amazonian forests. *Philosophical Transactions of the Royal Society B*, **363(1498)**, 1829-1838.

McAlpine, C.A., J. Syktus, J.G. Ryan, R.C. Deo, G.M. Mckeon, H.A. Mcgowan, and S.R. Phinn, 2009: A continent under stress: interactions, feedbacks and risks associated with impact of modified land cover on Australia's climate. *Global Change Biology*, **15(9)**, 2206-2223.

McCain, C.M. and R.K. Colwell, 2011: Assessing the threat to montane biodiversity from discordant shifts in temperature and precipitation in a changing climate. *Ecology Letters*, **14(12)**, 1236-1245.

McCarthy, M.P., M.J. Best, and R.A. Betts, 2010: Climate change in cities due to global warming and urban effects. *Geophysical Research Letters*, **37**, L09705.

McDougall, K.L., J.M. Alexander, S. Haider, A. Pauchard, N.G. Walsh, and C. Kueffer, 2011: Alien flora of mountains: global comparisons for the development of local preventive measures against plant invasions. *Diversity and Distributions*, **17(1)**, 103-111.

McDowell, N.G., D.J. Beerling, D.D. Breshears, R.A. Fisher, K.F. Raffa, and M. Stitt, 2011: The interdependence of mechanisms underlying climate-driven vegetation mortality. *Trends in Ecology & Evolution*, **26(10)**, 523-532.

McGeoch, M.A., S.H.M. Butchart, D. Spear, E. Marais, E.J. Kleynhans, A. Symes, J. Chanson, and M. Hoffmann, 2010: Global indicators of biological invasion: species numbers, biodiversity impact and policy responses. *Diversity and Distributions*, **16(1)**, 95-108.

McGuire, A.D., F.S. Chapin, C. Wirth, M. Apps, J. Bhatti, T. Callaghan, T.R. Christensen, J.S. Clein, M. Fukuda, T. Maximov, A. Onuchin, A. Shvidenko, E. Vaganov, J.G. Canadell, D.E. Pataki, and L.F. Pitelka, 2007: Responses of high latitude ecosystems to global change: potential consequences for the climate system. In: *Terrestrial Ecosystems in a Changing World* [Canadell, J.G., D.E. Pataki, and L.F. Pitelka (eds.)]. Global Change – The IGBP Series, Springer-Verlag, Berlin, Heidelberg, Germany, pp. 297-310.

McGuire, A.D., D.J. Hayes, D.W. Kicklighter, M. Manizza, Q. Zhuang, M. Chen, M.J. Follows, K.R. Gurney, J.W. McClelland, J.M. Melillo, B.J. Peterson, and R.G. Prinn, 2010: An analysis of the carbon balance of the Arctic Basin from 1997 to 2006. *Tellus Series B:Chemical and Physical Meteorology*, **62(5)**, 455-474.

McGuire, A.D., T.R. Christensen, D. Hayes, A. Heroult, E. Euskirchen, Y. Yi, J.S. Kimball, C. Koven, P. Lafleur, P.A. Miller, W. Oechel, P. Peylin, and M. Williams, 2012: An assessment of the carbon balance of arctic tundra: comparisons among observations, process models, and atmospheric inversions. *Biogeosciences Discussions*, **9(4)**, 4543-4594.

McKenzie, V.J. and A.C. Peterson, 2012: Pathogen pollution and the emergence of a deadly amphibian pathogen. *Molecular Ecology*, **21(21)**, 5151-5154.

McKinney, M., 2008: Effects of urbanization on species richness: a review of plants and animals. *Urban Ecosystems*, **11(2)**, 161-176.

McLachlan, J.S., J.S. Clark, and P.S. Manos, 2005: Molecular indicators of tree migration capacity under rapid climate change. *Ecology*, **86(8)**, 2088-2098.

McLaughlin, S.B., M. Nosal, S.D. Wullschleger, and G. Sun, 2007: Interactive effects of ozone and climate on tree growth and water use in a southern Appalachian forest in the USA. *New Phytologist*, **174(1)**, 109-124.

McMahon, S.M., S.P. Harrison, W.S. Armbruster, P.J. Bartlein, C.M. Beale, M.E. Edwards, J. Kattge, G. Midgley, X. Morin, and I.C. Prentice, 2011: Improving assessment and modelling of climate change impacts on global terrestrial biodiversity. *Trends in Ecology & Evolution*, **26(5)**, 249-259.

McMenamin, S.K. and L. Hannah, 2012: First extinctions on land. In: *Saving a Million Species: Extinction Risk from Climate Change* [Hannah, L. (ed.)]. Island Press, Washington, DC, USA, pp. 89-102.

Mehl, J.W., C.J. Geldenhuys, J. Roux, and M.J. Wingfield, 2010: Die-back of kiaat (*Pterocarpus angolensis*) in southern Africa: a cause for concern? *Southern Forests: a Journal of Forest Science*, **72(3-4)**, 121-132.

Meier, E.S., H. Lischke, D.R. Schmatz, and N.E. Zimmermann, 2012: Climate, competition and connectivity affect future migration and ranges of European trees. *Global Ecology and Biogeography*, **21(2)**, 164-178.

Menéndez, R., A. Gonzalez-Megias, O.T. Lewis, M.R. Shaw, and C.D. Thomas, 2008: Escape from natural enemies during climate-driven range expansion: a case study. *Ecological Entomology*, **33(3)**, 413-421.

Menge, D.N.L. and C.B. Field, 2007: Simulated global changes alter phosphorus demand in annual grassland. *Global Change Biology*, **13(12)**, 2582-2591.

Menzel, A., T.H. Sparks, N. Estrella, E. Koch, A. Aasa, R. Ahas, K. Alm-Kubler, P. Bissolli, O. Braslavska, A. Briede, F.M. Chmielewski, Z. Crepinsek, Y. Curnel, A. Dahl, C. Defila, A. Donnelly, Y. Filella, K. Jatcza, F. Mage, A. Mestre, O. Nordli, J. Penuelas, P. Pirinen, V. Remisova, H. Scheifinger, M. Striz, A. Susnik, A.J.H. Van Vliet, F.E. Wielgolaski, S. Zach, and A. Zust, 2006: European phenological response to climate change matches the warming pattern. *Global Change Biology*, **12(10)**, 1969-1976.

Mercado, L.M., N. Bellouin, S. Sitch, O. Boucher, C. Huntingford, M. Wild, and P.M. Cox, 2009: Impact of changes in diffuse radiation on the global land carbon sink. *Nature*, **458(7241)**, 1014-1017.

Merilä, J., 2012: Evolution in response to climate change: in pursuit of the missing evidence. *Bioessays*, **34(9)**, 811-818.

Meyers, E.M., B. Dobrowski, and C.L. Tague, 2010: Climate change impacts on flood frequency, intensity, and timing may affect trout species in Sagehen Creek, California. *Transactions of the American Fisheries Society*, **139(6)**, 1657-1664.

Meyfroidt, P. and E.F. Lambin, 2011: Global forest transition: prospects for an end to deforestation. *Annual Review of Environment and Resources*, **36**, 343-371.

Michaelian, M., E.H. Hogg, R.J. Hall, and E. Arsenault, 2011: Massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest. *Global Change Biology*, **17(6)**, 2084-2094.

Michalski, S.G., W. Durka, A. Jentsch, J. Kreyling, S. Pompe, O. Schweiger, E. Willner, and C. Beierkuhnlein, 2010: Evidence for genetic differentiation and divergent selection in an autotetraploid forage grass (*Arrhenatherum elatius*). *TAG Theoretical and Applied Genetics*, **120(6)**, 1151-1162.

Michelutti, N., A.P. Wolfe, R.D. Vinebrooke, B. Rivard, and J.P. Briner, 2005: Recent primary production increases in arctic lakes. *Geophysical Research Letters*, **32(19)**, L19715, doi:10.1029/2005GL023693.

Midgley, G.F., I.D. Davies, C.H. Albert, R. Altwegg, L. Hannah, G.O. Hughes, L.R. O'Halloran, C. Seo, J.H. Thorne, and W. Thuiller, 2010: BioMove – an integrated platform simulating the dynamic response of species to environmental change. *Ecography*, **33(3)**, 612-616.

Mihoub, J.B., N.G. Mouawad, P. Pilard, F. Jiguet, M. Low, and C. Teplitsky, 2012: Impact of temperature on the breeding performance and selection patterns in lesser kestrels *Falco naumanni*. *Journal of Avian Biology*, **43(5)**, 472-480.

Miles, L., A.C. Newton, R.S. DeFries, C. Ravilious, I. May, S. Blyth, V. Kapos, and J.E. Gordon, 2006: A global overview of the conservation status of tropical dry forests. *Journal of Biogeography*, **33(3)**, 491-505.

Millar, C., R. Westfall, D. Delany, J. King, and L. Graumlich, 2004: Response of subalpine conifers in the Sierra Nevada, California, U.S.A., to 20th-century warming and decadal climate variability. *Arctic, Antarctic, and Alpine Research*, **36(2)**, 181-200.

Millar, C.I., R.D. Westfall, D.L. Delany, M.J. Bokach, A.L. Flint, and L.E. Flint, 2012: Forest mortality in high-elevation whitebark pine (*Pinus albicaulis*) forests of eastern California, USA; influence of environmental context, bark beetles, climatic water deficit, and warming. *Canadian Journal of Forest Research / Revue Canadienne De Recherche Forestiere*, **42(4)**, 749-765.

Millennium Ecosystem Assessment, 2003: *Ecosystems and Human Well-being: A Framework for Assessment*. Island Press, Washington, DC, USA, 212 pp.

Millennium Ecosystem Assessment, 2005a: *Ecosystems and Human Well-being: Desertification Synthesis*. World Resources Institute, Washington, DC, USA, 26 pp.

Millennium Ecosystem Assessment, 2005b: *Ecosystems and Human Well-being: Biodiversity Synthesis*. World Resources Institute, Washington, DC, USA, 86 pp.

Millennium Ecosystem Assessment, 2005c: *Ecosystems and Human Well-being: Current State and Trends*, *Vol. 1*. Island Press, Washington, DC, USA, 917 pp.

Millennium Ecosystem Assessment, 2005d: *Ecosystems and Human Well-being: Scenerios*, *Vol. 2*. Island Press, Washington, DC, USA, 560 pp.

Millennium Ecosystem Assessment, 2005e: *Ecosystems and Human Well-being: Policy Responses*, *Vol. 3*. Island Press, Washington, DC, USA, 621 pp.

Miller-Rushing, A.J., T.L. Lloyd-Evans, R.B. Primack, and P. Satzinger, 2008: Bird migration times, climate change, and changing population sizes. *Global Change Biology*, **14(9)**, 1959-1972.

Mills, G., F. Hayes, S. Wilkinson, and W.J. Davies, 2009: Chronic exposure to increasing background ozone impairs stomatal functioning in grassland species. *Global Change Biology*, **15(6)**, 1522-1533.

Mills, G., F. Hayes, D. Simpson, L. Emberson, D. Norris, H. Harmens, and P. Buker, 2011: Evidence of widespread effects of ozone on crops and (semi-)natural vegetation in Europe (1990-2006) in relation to AOT40-and flux-based risk maps. *Global Change Biology*, **17(1)**, 592-613.

Minnich, R.A., 2007: Southern California conifer forests. In: *Terrestrial Vegetation of California* [Barbour, M., T. Keeler-Wolf, and A. A. Schoenherr (eds.)]. University of California Press, Berkeley, CA, USA, pp. 502-538.

Minteer, B.A. and J.P. Collins, 2010: Move it or lose it? The ecological ethics of relocating species under climate change. *Ecological Applications*, **20(7)**, 1801-1804.

Miranda, J.D., F.M. Padilla, and F.I. Pugnaire, 2009: Response of a Mediterranean semiarid community to changing patterns of water supply. *Perspectives in Plant Ecology Evolution and Systematics*, **11(4)**, 255-266.

Mishra, V., K.A. Cherkauer, D. Niyogi, M. Lei, B.C. Pijanowski, D.K. Ray, L.C. Bowling, and G. Yang, 2010: A regional scale assessment of land use/land cover and climatic changes on water and energy cycle in the upper Midwest United States. *International Journal of Climatology*, **30(13)**, 2025-2044.

Mitas, C.M. and A. Clement, 2005: Has the Hadley cell been strengthening in recent decades? *Geophysical Research Letters*, **32(3)**, L030809, doi:10.1029/2004GL021765.

Mitchard, E.T.A., S.S. Saatchi, F.F. Gerard, S.L. Lewis, and P. Meir, 2009: Measuring woody encroachment along a forest-savanna boundary in Central Africa. *Earth Interactions*, **13(8)**, 1-29.

Mitchell, T.D. and P.D. Jones, 2005: An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology*, **25(6)**, 693-712.

Miyake, S., M. Renouf, A. Peterson, C. McAlpine, and C. Smith, 2012: Land-use and environmental pressures resulting from current and future bioenergy crop expansion: a review. *Journal of Rural Studies*, **28(4)**, 650-658.

Mohan, J.E., L.H. Ziska, W.H. Schlesinger, R.B. Thomas, R.C. Sicher, K. George, and J.S. Clark, 2006: Biomass and toxicity responses of poison ivy (*Toxicodendron radicans*) to elevated atmospheric CO_2. *Proceedings of the National Academy of Sciences of the United States of America*, **103(24)**, 9086-9089.

Moiseyev, A., B. Solberg, A.M.I. Kallio, and M. Lindner, 2011: An economic analysis of the potential contribution of forest biomass to the EU RES target and its implications for the EU forest industries. *Journal of Forest Economics*, **17(2)**, 197-213.

Moleele, N.M., S. Ringrose, W. Matheson, and C. Vanderpost, 2002: More woody plants? The status of bush encroachment in Botswana's grazing areas. *Journal of Environmental Management*, **64(1)**, 3-11.

Møller, A.P., D. Rubolini, and E. Lehikoinen, 2008: Populations of migratory bird species that did not show a phenological response to climate change are declining. *Proceedings of the National Academy of Sciences of the United States of America*, **105(42)**, 16195-16200.

Monahan, W.B. and M.W. Tingley, 2012: Niche tracking and rapid establishment of distributional equilibrium in the house sparrow show potential responsiveness of species to climate change. *PLoS One*, **7(7)**, e42097, doi:10.1371/journal.pone.0042097.

Monteith, D.T., J.L. Stoddard, C.D. Evans, H.A. de Wit, M. Forsius, T. Hogasen, A. Wilander, B.L. Skjelkvale, D.S. Jeffries, J. Vuorenmaa, B. Keller, J. Kopacek, and J. Vesely, 2007: Dissolved organic carbon trends resulting from changes in atmospheric deposition chemistry. *Nature*, **450(7169)**, 537-540.

Montoya, J.M. and D. Raffaelli, 2010: Climate change, biotic interactions and ecosystem services. *Philosophical Transactions of the Royal Society B*, **365(1549)**, 2013-2018.

Mooney, H.A., S.H. Bullock, and E. Medina, 1995: Introduction. In: *Seasonally Dry Tropical Forests* [Bullock, S.H., H.A. Mooney, and E. Medina (eds.)]. Cambridge University Press, Cambridge, UK, pp. 1-8.

Moore, S., C.D. Evans, S.E. Page, M.H. Garnett, T.G. Jones, C. Freeman, A. Hooijer, A.J. Wiltshire, S.H. Limin, and V. Gauci, 2013: Deep instability of deforested tropical peatlands revealed by fluvial organic carbon fluxes. *Nature*, **493(7434)**, 660-663.

Morecroft, M.D., H.Q.P. Crick, S.J. Duffield, and N.A. Macgregor, 2012: Resilience to climate change: translating principles into practice. *Journal of Applied Ecology*, **49(3)**, 547-551.

Morin, X. and W. Thuiller, 2009: Comparing niche- and process-based models to reduce prediction uncertainty in species range shifts under climate change. *Ecology*, **90(5)**, 1301-1313.

Morin, X., C. Augspurger, and I. Chuine, 2007: Process-based modeling of species' distributions: what limits temperate tree species' range boundaries? *Ecology*, **88(9)**, 2280-2291.

Moritz, C. and R. Agudo, 2013: The future of species under climate change: resilience or decline? *Science*, **341(6145)**, 504-508.

Moritz, M.A., M.A. Parisien, E. Batllori, M.A. Krawchuk, J. Van Dorn, D.J. Ganz, and K. Hayhoe, 2012: Climate change and disruptions to global fire activity. *Ecosphere*, **3(6)**, 49, doi:10.1890/ES11-00345.

Morrison, J., M.C. Quick, and M.G.G. Foreman, 2002: Climate change in the Fraser River watershed: flow and temperature projections. *Journal of Hydrology*, **263(1-4)**, 230-244.

Mueller, A.D., G.A. Islebe, M.B. Hillesheim, D.A. Grzesik, F.S. Anselmetti, D. Ariztegui, M. Brenner, J.H. Curtis, D.A. Hodell, and K.A. Venz, 2009: Climate drying and associated forest decline in the lowlands of northern Guatemala during the late Holocene. *Quaternary Research*, **71(2)**, 133-141.

Mueller, D.R., P. Van Hove, D. Antoniades, M.O. Jeffries, and W.F. Vincent, 2009: High Arctic lakes as sentinel ecosystems: cascading regime shifts in climate, ice cover, and mixing. *Limnology and Oceanography*, **54(6)**, 2371-2385.

Mueller, R.C., C.M. Scudder, M.E. Porter, R.T. Trotter, C.A. Gehring, and T.G. Whitham, 2005: Differential tree mortality in response to severe drought: evidence for long-term vegetation shifts. *Journal of Ecology*, **93(6)**, 1085-1093.

Muhlfeld, C.C., J.J. Giersch, F.R. Hauer, G.T. Pederson, G. Luikart, D.P. Peterson, C.C. Downs, and D.B. Fagre, 2011: Climate change links fate of glaciers and an endemic alpine invertebrate. *Climatic Change*, **106(2)**, 337-345.

Muñoz-Robles, C., N. Reid, M. Tighe, S.V. Briggs, and B. Wilson, 2011: Soil hydrological and erosional responses in areas of woody encroachment, pasture and woodland in semi-arid Australia. *Journal of Arid Environments*, **75(10)**, 936-945.

Murdiyarso, D., K. Hergoualc'h, and L.V. Verchot, 2010: Opportunities for reducing greenhouse gas emissions in tropical peatlands. *Proceedings of the National Academy of Sciences of the United States of America*, **107(46)**, 19655-19660.

Musolin, D.L., D. Tougou, and K. Fujisaki, 2010: Too hot to handle? Phenological and life-history responses to simulated climate change of the southern green stink bug *Nezara viridula* (Heteroptera: Pentatomidae). *Global Change Biology*, **16(1)**, 73-87.

Myers-Smith, I.H., B.C. Forbes, M. Wilmking, M. Hallinger, T. Lantz, D. Blok, K.D. Tape, M. Macias-Fauria, U. Sass-Klaassen, E. Levesque, S. Boudreau, P. Ropars, L. Hermanutz, A. Trant, L.S. Collier, S. Weijers, J. Rozema, S.A. Rayback, N.M. Schmidt, G. Schaepman-Strub, S. Wipf, C. Rixen, C.B. Menard, S. Venn, S. Goetz, L. Andreu-Hayles, S. Elmendorf, V. Ravolainen, J. Welker, P. Grogan, H.E. Epstein, and D.S. Hik, 2011: Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities. *Environmental Research Letters*, **6(4)**, 045509, doi:10.1088/1748-9326/6/4/045509.

Nabuurs, G.J., G.M. Hengeveld, D.C. van der Werf, and A.H. Heidema, 2010: European forest carbon balance assessed with inventory based methods – an introduction to a special section. *Forest Ecology and Management*, **260(3)**, 239-240.

Naito, A.T. and D.M. Cairns, 2011: Patterns and processes of global shrub expansion. *Progress in Physical Geography*, **35(4)**, 423-442.

Nakazawa, T. and H. Doi, 2012: A perspective on match/mismatch of phenology in community contexts. *Oikos*, **121(4)**, 489-495.

Nathan, R., 2006: Long-distance dispersal of plants. *Science*, **313(5788)**, 786-788.

Nathan, R., N. Horvitz, Y.P. He, A. Kuparinen, F.M. Schurr, and G.G. Katul, 2011: Spread of North American wind-dispersed trees in future environments. *Ecology Letters*, **14(3)**, 211-219.

Nemet, G.F., 2009: Net radiative forcing from widespread deployment of photovoltaics. *Environmental Science and Technology*, **43(6)**, 2173-2178.

Nepstad, D.C., I.M. Tohver, D. Ray, P. Moutinho, and G. Cardinot, 2007: Mortality of large trees and lianas following experimental drought in an Amazon forest. *Ecology*, **88(9)**, 2259-2269.

Nepstad, D.C., C.M. Stickler, B. Soares, and F. Merry, 2008: Interactions among Amazon land use, forests and climate: prospects for a near-term forest tipping point. *Philosophical Transactions of the Royal Society B*, **363(1498)**, 1737-1746.

Nepstad, D.C., B.S. Soares, F. Merry, A. Lima, P. Moutinho, J. Carter, M. Bowman, A. Cattaneo, H. Rodrigues, S. Schwartzman, D.G. McGrath, C.M. Stickler, R. Lubowski, P. Piris-Cabezas, S. Rivero, A. Alencar, O. Almeida, and O. Stella, 2009: The end of deforestation in the Brazilian Amazon. *Science*, **326(5958)**, 1350-1351.

Nepstad, D.C., W. Boyd, C.M. Stickler, T. Bezerra, and A.A. Azevedo, 2013: Responding to climate change and the global land crisis: REDD+, market transformation and low-emissions rural development. *Philosophical Transactions of the Royal Society B*, **368(1619)**, 20120167, doi:10.1098/rstb.2012.0167.

Ni, J., 2011: Impacts of climate change on Chinese ecosystems: key vulnerable regions and potential thresholds. *Regional Environmental Change*, **11**, S49-S64.

Niboyet, A., J.R. Brown, P. Dijkstra, J.C. Blankinship, P.W. Leadley, X. Le Roux, L. Barthes, R.L. Barnard, C.B. Field, and B.A. Hungate, 2011: Global change could amplify fire effects on soil greenhouse gas emissions. *PLoS One*, **6(6)**, e20105, doi:10.1371/journal.pone.0020105.

Nicholls, R.J., 2004: Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios. *Global Environmental Change: Human and Policy Dimensions*, **14(1)**, 69-86.

Nielsen, U.N. and D.H. Wall, 2013: The future of soil invertebrate communities in polar regions: different climate change responses in the Arctic and Antarctic? *Ecology Letters*, **16(3)**, 409-419.

Nilsson, C., C.A. Reidy, M. Dynesius, and C. Revenga, 2005: Fragmentation and flow regulation of the world's large river systems. *Science*, **308(5720)**, 405-408.

Nock, C.A., P.J. Baker, W. Wanek, A. Leis, M. Grabner, S. Bunyavejchewin, and P. Hietz, 2011: Long-term increases in intrinsic water-use efficiency do not lead to increased stem growth in a tropical monsoon forest in western Thailand. *Global Change Biology*, **17(2)**, 1049-1063.

Nogues-Bravo, D., R. Ohlemuller, P. Batra, and M.B. Araujo, 2010: Climate predictors of Late Quaternary extinctions. *Evolution*, **64(8)**, 2442-2449.

Norberg, J., M.C. Urban, M. Vellend, C.A. Klausmeier, and N. Loeuille, 2012: Eco-evolutionary responses of biodiversity to climate change. *Nature Climate Change*, **2(10)**, 747-751.

Norby, R.J. and D.R. Zak, 2011: Ecological lessons from free-air CO_2 enrichment (FACE) experiments. *Annual Review of Ecology, Evolution, and Systematics*, **42**, 181-203.

Normand, S., U.A. Treier, C. Randin, P. Vittoz, A. Guisan, and J.C. Svenning, 2009: Importance of abiotic stress as a range-limit determinant for European plants: insights from species responses to climatic gradients. *Global Ecology and Biogeography*, **18(4)**, 437-449.

Nowicki, P., A. Pepkowska, J. Kudlek, P. Skorka, M. Witek, J. Settele, and M. Woyciechowski, 2007: From metapopulation theory to conservation recommendations: lessons from spatial occurrence and abundance patterns of Maculinea butterflies. *Biological Conservation*, **140(1-2)**, 119-129.

O'Connor, F.M., O. Boucher, N. Gedney, C.D. Jones, G.A. Folberth, R. Coppell, P. Friedlingstein, W.J. Collins, J. Chappellaz, J. Ridley, and C.E. Johnson, 2010: Possible role of wetlands, permafrost, and methane hydrates in the methane cycle under future climate change: a review. *Reviews of Geophysics*, **48(4)**, RG4005, doi:10.1029/2010RG000326.

O'Donnell, J.A., J.W. Harden, A.D. McGuire, M.Z. Kanevskiy, M.T. Jorgenson, and X.M. Xu, 2011: The effect of fire and permafrost interactions on soil carbon accumulation in an upland black spruce ecosystem of interior Alaska: implications for post-thaw carbon loss. *Global Change Biology*, **17(3)**, 1461-1474.

O'Halloran, T.L., B.E. Law, M.L. Goulden, Z. Wang, J.G. Barr, C. Schaaf, M. Brown, J.D. Fuentes, M. Göckede, A. Black, and V. Engel, 2012: Radiative forcing of natural forest disturbances. *Global Change Biology*, **18(2)**, 555-565.

O'Reilly, C.M., S.R. Alin, P.D. Plisnier, A.S. Cohen, and B.A. McKee, 2003: Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa. *Nature*, **424(6950)**, 766-768.

Obersteiner, M., H. Böttcher, and Y. Yamagata, 2010: Terrestrial ecosystem management for climate change mitigation. *Current Opinion in Environmental Sustainability*, **2(4)**, 271-276.

OECD and FAO, 2010: *OECD-FAO Agricultural Outlook 2010-2019.* Organisation for Economic Co-operation and Development (OECD) and the Food and Agriculture Organization of the United Nations (FAO), OECD Publishing, Paris, France, 247 pp.

Ogawa-Onishi, Y., P.M. Berry, and N. Tanaka, 2010: Assessing the potential impacts of climate change and their conservation implications in Japan: a case study of conifers. *Biological Conservation*, **143(7)**, 1728-1736.

Oleszczuk, R., K. Regina, L. Szajdak, H. Höper, and V. Maryganova, 2008: Impacts of agricultural utilization of peat soils on the greenhouse gas balance. In: *Peatlands and Climate Change* [Strack, M. (ed.)]. International Peat Society, Jyväskylä, Finland, pp. 70-97.

Oliver, R.J., J.W. Finch, and G. Taylor, 2009: Second generation bioenergy crops and climate change: a review of the effects of elevated atmospheric CO_2 and drought on water use and the implications for yield. *Global Change Biology Bioenergy*, **1(2)**, 97-114.

Oliver, T., J.K. Hill, C.D. Thomas, T. Brereton, and D.B. Roy, 2009: Changes in habitat specificity of species at their climatic range boundaries. *Ecology Letters*, **12(10)**, 1091-1102.

Oliver, T.H., S. Gillings, M. Girardello, G. Rapacciuolo, T.M. Brereton, G.M. Siriwardena, D.B. Roy, R. Pywell, and R.J. Fuller, 2012a: Population density but not stability can be predicted from species distribution models. *Journal of Applied Ecology*, **49(3)**, 581-590.

Oliver, T.H., R.J. Smithers, S. Bailey, C.A. Walmsley, and K. Watts, 2012b: A decision framework for considering climate change adaptation in biodiversity conservation planning. *Journal of Applied Ecology*, **49(6)**, 1247-1255.

Oltmans, S.J., A.S. Lefohn, J.M. Harris, D.W. Tarasick, A.M. Thompson, H. Wernli, B.J. Johnson, P.C. Novelli, S.A. Montzka, J.D. Ray, L.C. Patrick, C. Sweeney, A. Jefferson, T. Dann, and J. Davies, 2006: Long term changes in tropospheric ozone. *Atmospheric Environment*, **40(17)**, 3156-3173.

Ooi, M.K.J., T.D. Auld, and A.J. Denham, 2009: Climate change and bet-hedging: interactions between increased soil temperatures and seed bank persistence. *Global Change Biology*, **15(10)**, 2375-2386.

Ormerod, S.J., 2009: Climate change, river conservation and the adaptation challenge. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **19(6)**, 609-613.

Osawa, A., O.A. Zyryanova, Y. Matsuura, T. Kajimoto, and R.W. Wein, 2010: *Permafrost Ecosystems: Siberian Larch Forests*. Springer, New York, NY, USA, 502 pp.

Ozgul, A., D.Z. Childs, M.K. Oli, K.B. Armitage, D.T. Blumstein, L.E. Olson, S. Tuljapurkar, and T. Coulson, 2010: Coupled dynamics of body mass and population growth in response to environmental change. *Nature*, **466(7305)**, 482-485.

Pacifici, M., L. Santini, M. Di Marco, D. Baisero, L. Francucci, G. Grottolo Marassini, P. Visconti, and C. Rondinini, 2013: Generation lengths for mammals. *Nature Conservation*, **5(2013)**, 89-94, doi:10.3897/natureconservation.5.5734.

Paerl, H.W., N.S. Hall, and E.S. Calandrino, 2011: Controlling harmful cyanobacterial blooms in a world experiencing anthropogenic and climatic-induced change. *Science of the Total Environment*, **409(10)**, 1739-1745.

Page, S.E., F. Siegert, J.O. Rieley, H.D. Boehm, A. Jaya, and S. Limin, 2002: The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*, **420(6911)**, 61-65.

Page, S.E., J.O. Rieley, and C.J. Banks, 2011: Global and regional importance of the tropical peatland carbon pool. *Global Change Biology*, **17(2)**, 798-818.

Pan, Y., R. Birdsey, J. Hom, and K. McCullough, 2009: Separating effects of changes in atmospheric composition, climate and land-use on carbon sequestration of US Mid-Atlantic temperate forests. *Forest Ecology and Management*, **259(2)**, 151-164.

Pan, Y., R. Birdsey, J. Fang, R. Houghton, P. Kauppi, W.A. Kurz, O.L. Phillips, A. Shvidenko, S.L. Lewis, J.G. Canadell, P. Ciais, R.B. Jackson, S. Pacala, A.D. McGuire, S. Piao, A. Rautiainen, S. Sitch, and D. Hayes, 2011: A large and persistent carbon sink in the world's forests. *Science*, **333(6045)**, 988-993.

Parent, M.B. and D. Verbyla, 2010: The browning of Alaska's boreal forest. *Remote Sensing*, **2(12)**, 2729-2747.

Parker-Allie, F., C.F. Musil, and W. Thuiller, 2009: Effects of climate warming on the distributions of invasive Eurasian annual grasses: a South African perspective. *Climatic Change*, **94(1-2)**, 87-103.

Parker, B.R., R.D. Vinebrooke, and D.W. Schindler, 2008: Recent climate extremes alter alpine lake ecosystems. *Proceedings of the National Academy of Sciences of the United States of America*, **105(35)**, 12927-12931.

Parmesan, C., 2006: Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology Evolution and Systematics*, **37**, 637-669.

Parmesan, C., 2007: Influences of species, latitudes and methodologies on estimates of phenological response to global warming. *Global Change Biology*, **13(9)**, 1860-1872.

Parmesan, C. and G. Yohe, 2003: A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, **421(6918)**, 37-42.

Pataki, D.E., M.M. Carreiro, J. Cherrier, N.E. Grulke, V. Jennings, S. Pincetl, R.V. Pouyat, T.H. Whitlow, and W.C. Zipperer, 2011: Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions. *Frontiers in Ecology and the Environment*, **9(1)**, 27-36.

Pateman, R.M., J.K. Hill, D.B. Roy, R. Fox, and C.D. Thomas, 2012: Temperature-dependent alterations in host use drive rapid range expansion in a butterfly. *Science*, **336(6084)**, 1028-1030.

Paterson, J.S., M.B. Araujo, P.M. Berry, J.M. Piper, and M.D.A. Rounsevell, 2008: Mitigation, adaptation, and the threat to biodiversity. *Conservation Biology*, **22(5)**, 1352-1355.

Pauli, H., M. Gottfried, K. Reiter, C. Klettner, and G. Grabherr, 2007: Signals of range expansions and contractions of vascular plants in the high Alps: observations (1994-2004) at the GLORIA master site Schrankogel, Tyrol, Austria. *Global Change Biology*, **13**, 147-156.

Pauli, H., M. Gottfried, S. Dullinger, O. Abdaladze, M. Akhalkatsi, J.L.B. Alonso, G. Coldea, J. Dick, B. Erschbamer, R.F. Calzado, D. Ghosn, J.I. Holten, R. Kanka, G. Kazakis, J. Kollar, P. Larsson, P. Moiseev, D. Moiseev, U. Molau, J.M. Mesa, L. Nagy, G. Pelino, M. Puscas, G. Rossi, A. Stanisci, A.O. Syverhuset, J.P. Theurillat, M. Tomaselli, P. Unterluggauer, L. Villar, P. Vittoz, and G. Grabherr, 2012: Recent plant diversity changes on Europe's mountain summits. *Science*, **336(6079)**, 353-355.

Pauls, S.U., C. Nowak, M. Bálint, and M. Pfenninger, 2013: The impact of global climate change on genetic diversity within populations and species. *Molecular Ecology*, **22(4)**, 925-946.

Paun, O., R.M. Bateman, M.F. Fay, M. Hedren, L. Civeyrel, and M.W. Chase, 2010: Stable epigenetic effects impact adaptation in allopolyploid Orchids (*Dactylorhiza*: Orchidaceae). *Molecular Biology and Evolution*, **27(11)**, 2465-2473.

Payette, S., 2007: Contrasted dynamics of northern Labrador tree lines caused by climate change and migrational lag. *Ecology*, **88(3)**, 770-780.

Payette, S. and L. Filion, 1985: White spruce expansion at the tree line and recent climatic change. *Canadian Journal of Forest Research / Revue Canadienne De Recherche Forestiere*, **15(1)**, 241-251.

Pearce-Higgins, J.W., L. Stephen, A. Douse, and R.H.W. Langston, 2012: Greater impacts of wind farms on bird populations during construction than subsequent operation: results of a multi-site and multi-species analysis. *Journal of Applied Ecology*, **49(2)**, 386-394.

Pearlstine, L.G., E.V. Pearlstine, and N.G. Aumen, 2010: A review of the ecological consequences and management implications of climate change for the Everglades. *Journal of the North American Benthological Society*, **29(4)**, 1510-1526.

Pearman, P.B., C.F. Randin, O. Broennimann, P. Vittoz, W.O. van der Knaap, R. Engler, G. Le Lay, N.E. Zimmermann, and A. Guisan, 2008: Prediction of plant species distributions across six millennia. *Ecology Letters*, **11(4)**, 357-369.

Pearson, R.G., 2006: Climate change and the migration capacity of species. *Trends in Ecology & Evolution*, **21(3)**, 111-113.

Pearson, R.G., 2011: *Driven to Extinction: The Impact of Climate Change on Biodiversity*. Sterling, New York, NY, USA, 263 pp.

Pearson, R.G. and T.P. Dawson, 2003: Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Global Ecology and Biogeography*, **12(5)**, 361-371.

Pearson, R.G., S.J. Phillips, M.M. Loranty, P.S.A. Beck, T. Damoulas, S.J. Knight, and S.J. Goetz, 2013: Shifts in Arctic vegetation and associated feedbacks under climate change. *Nature Climate Change*, **3**, 673-677.

Pechony, O. and D.T. Shindell, 2010: Driving forces of global wildfires over the past millennium and the forthcoming century. *Proceedings of the National Academy of Sciences of the United States of America*, **107(45)**, 19167-19170.

Pederson, G.T., L.J. Graumlich, D.B. Fagre, T. Kipfer, and C.C. Muhlfeld, 2010: A century of climate and ecosystem change in Western Montana: what do temperature trends portend? *Climatic Change*, **98(1-2)**, 133-154.

Pedlar, J.H., D.W. McKenney, I. Aubin, T. Beardmore, J. Beaulieu, L. Iverson, G.A. O'Neill, R.S. Winder, and C. Ste-Marie, 2012: Placing forestry in the assisted migration debate. *BioScience*, **62(9)**, 835-842.

Peltzer, D.A., R.B. Allen, G.M. Lovett, D. Whitehead, and D.A. Wardle, 2010: Effects of biological invasions on forest carbon sequestration. *Global Change Biology*, **16(2)**, 732-746.

Peng, C., X. Zhou, S. Zhao, X. Wang, B. Zhu, S. Piao, and J. Fang, 2009: Quantifying the response of forest carbon balance to future climate change in NE China: model validation and prediction. *Global and Planetary Change*, **66(3-4)**, 179-194.

Peng, C., Z. Ma, X. Lei, Q. Zhu, H. Chen, W. Wang, S. Liu, W. Li, X. Fang, and X. Zhou, 2011: A drought-induced pervasive increase in tree mortality across Canada's boreal forests. *Nature Climate Change*, **1(9)**, 467-471.

Peng, J., W. Dong, Y. Wenping, Y. Zhang, and J. Li, 2013: Effects of increased CO_2 on land water balance from 1850 to 1989. *Theoretical and Applied Climatology*, **111(3-4)**, 483-495.

Peñuelas, J. and M. Boada, 2003: A global change-induced biome shift in the Montseny mountains (NE Spain). *Global Change Biology*, **9(2)**, 131-140.

Peñuelas, J., C. Gordon, L. Llorens, T. Nielsen, A. Tietema, C. Beier, P. Bruna, B. Emmett, M. Estiarte, and A. Gorissen, 2004: Nonintrusive field experiments show different plant responses to warming and drought among sites, seasons, and species in a north-south European gradient. *Ecosystems*, **7(6)**, 598-612.

Peñuelas, J., P. Prieto, C. Beier, C. Cesaraccio, P. de Angelis, G. de Dato, B.A. Emmett, M. Estiarte, J. Garadnai, A. Gorissen, E.K. Lang, G. Kroel-Dulay, L. Llorens, G. Pellizzaro, T. Riis-Nielsen, I.K. Schmidt, C. Sirca, A. Sowerby, D. Spano, and A. Tietema, 2007: Response of plant species richness and primary productivity in shrublands along a north-south gradient in Europe to seven years of experimental warming and drought: reductions in primary productivity in the heat and drought year of 2003. *Global Change Biology*, **13(12)**, 2563-2581.

Peñuelas, J., J.G. Canadell, and R. Ogaya, 2011: Increased water-use efficiency during the 20th century did not translate into enhanced tree growth. *Global Ecology and Biogeography*, **20(4)**, 597-608.

Peñuelas, J., J. Sardans, A. Rivas-Ubach, and I.A. Janssens, 2012: The human-induced imbalance between C, N and P in Earth's life system. *Global Change Biology*, **18(1)**, 3-6.

Peñuelas, J., J. Sardans, M. Estiarte, R. Ogaya, J. Carnicer, M. Coll, A. Barbeta, A. Rivas-Ubach, J. Llusia, M. Garbulsky, I. Filella, and A.S. Jump, 2013: Evidence of current impact of climate change on life: a walk from genes to the biosphere. *Global Change Biology*, **19(8)**, 2303-2338.

Pereira, H.M., P.W. Leadley, V. Proenca, R. Alkemade, J.P.W. Scharlemann, J.F. Fernandez-Manjarres, M.B. Araujo, P. Balvanera, R. Biggs, W.W.L. Cheung, L. Chini, H.D. Cooper, E.L. Gilman, S. Guenette, G.C. Hurtt, H.P. Huntington, G.M. Mace, T. Oberdorff, C. Revenga, P. Rodrigues, R.J. Scholes, U.R. Sumaila, and M. Walpole, 2010: Scenarios for global biodiversity in the 21st century. *Science*, **330(6010)**, 1496-1501.

Péron, G., J.E. Hines, J.D. Nichols, W.L. Kendall, K.A. Peters, and D.S. Mizrahi, 2013: Estimation of bird and bat mortality at wind-power farms with superpopulation models. *Journal of Applied Ecology*, **50(4)**, 902-911.

Perry, L.G., D.C. Andersen, L.V. Reynolds, S.M. Nelson, and P.B. Shafroth, 2012: Vulnerability of riparian ecosystems to elevated CO_2 and climate change in arid and semiarid western North America. *Global Change Biology*, **18(3)**, 821-842.

Peterken, G.F. and E.P. Mountford, 1996: Effects of drought on beech in Lady Park Wood, an unmanaged mixed deciduous woodland. *Forestry*, **69(2)**, 125-136.

Peters, D.P.C., J.E. Herrick, H.C. Monger, and H.T. Huang, 2010: Soil-vegetation-climate interactions in arid landscapes: effects of the North American monsoon on grass recruitment. *Journal of Arid Environments*, **74(5)**, 618-623.

Peterson, M.A. and R.F. Denno, 1998: The influence of dispersal and diet breadth on patterns of genetic isolation by distance in phytophagous insects. *American Naturalist*, **152(3)**, 428-446.

Peterson, A.T., A. Stewart, K.I. Mohamed, and M.B. Araujo, 2008: Shifting global invasive potential of European plants with climate change. *PLoS One*, **3(6)**, e2441, doi:10.1371/journal.pone.0002441.

Peterson, A.T.S., J., R.G. Pearson, R.P. Anderson, E. Martínez-Meyer, M. Nakamura, and M.B. Araújo, 2011: *Ecological Niches and Geographic Distributions*. Princeton University Press, Princeton, NJ, USA, 328 pp.

Petit, B. and F. Montagnini, 2006: Growth in pure and mixed plantations of tree species used in reforesting rural areas of the humid region of Costa Rica, Central America. *Forest Ecology and Management*, **233(2-3)**, 338-343.

Petitpierre, B., C. Kueffer, O. Broennimann, C. Randin, C. Daehler, and A. Guisan, 2012: Climatic niche shifts are rare among terrestrial plant invaders. *Science*, **335(6074)**, 1344-1348.

Peylin, P., P. Bousquet, C. Le Quere, P. Friedlingstein, G. McKinley, N. Gruber, P. Rayner, and P. Ciais, 2005: Multiple constraints on regional CO_2 flux variations over land and oceans. *Global Biogeochemical Cycles*, **19(1)**, GB1011, doi:10.1029/2003GB002214.

Phillimore, A.B., J.D. Hadfield, O.R. Jones, and R.J. Smithers, 2010: Differences in spawning date between populations of common frog reveal local adaptation. *Proceedings of the National Academy of Sciences of the United States of America*, **107(18)**, 8292-8297.

Phillips, O.L., R.V. Martinez, L. Arroyo, T.R. Baker, T. Killeen, S.L. Lewis, Y. Malhi, A.M. Mendoza, D. Neill, P.N. Vargas, M. Alexiades, C. Ceron, A. Di Fiore, T. Erwin, A. Jardim, W. Palacios, M. Saldias, and B. Vinceti, 2002: Increasing dominance of large lianas in Amazonian forests. *Nature*, **418(6899)**, 770-774.

Phillips, O.L., R. Vásquez Martínez, A. Monteagudo Mendoza, T. Baker, and P. Núñez-Vargas, 2005: Large lianas as hyperdynamic elements of the tropical forest canopy. *Ecology*, **86(5)**, 1250-1258.

Phillips, O.L., L. Aragao, S.L. Lewis, J.B. Fisher, J. Lloyd, G. Lopez-Gonzalez, Y. Malhi, A. Monteagudo, J. Peacock, C.A. Quesada, G. van der Heijden, S. Almeida, I. Amaral, L. Arroyo, G. Aymard, T.R. Baker, O. Banki, L. Blanc, D. Bonal, P. Brando, J. Chave, A.C.A. de Oliveira, N.D. Cardozo, C.I. Czimczik, T.R. Feldpausch, M.A. Freitas, E. Gloor, N. Higuchi, E. Jimenez, G. Lloyd, P. Meir, C. Mendoza, A. Morel, D.A. Neill, D. Nepstad, S. Patino, M.C. Penuela, A. Prieto, F. Ramirez, M. Schwarz, J. Silva, M. Silveira, A.S. Thomas, H. ter Steege, J. Stropp, R. Vasquez, P. Zelazowski, E.A. Davila, S. Andelman, A. Andrade, K.J. Chao, T. Erwin, A. Di Fiore, E. Honorio, H. Keeling, T.J. Killeen, W.F. Laurance, A.P. Cruz, N.C.A. Pitman, P.N. Vargas, H. Ramirez-Angulo, A. Rudas, R. Salamao, N. Silva, J. Terborgh, and A. Torres-Lezama, 2009: Drought sensitivity of the Amazon rainforest. *Science*, **323(5919)**, 1344-1347.

Phillips, O.L., G. van der Heijden, S.L. Lewis, G. Lopez-Gonzalez, L.E.O.C. Aragao, J. Lloyd, Y. Malhi, A. Monteagudo, S. Almeida, E. Alvarez Davila, I. Amaral, S. Andelman, A. Andrade, L. Arroyo, G. Aymard, T.R. Baker, L. Blanc, D. Bonal, A.C. Alves de Oliveira, K.-J. Chao, N. Davila Cardozo, L. da Costa, T.R. Feldpausch, J.B. Fisher, N.M. Fyllas, M.A. Freitas, D. Galbraith, E. Gloor, N. Higuchi, E. Honorio, E. Jimenez, H. Keeling, T.J. Killeen, J.C. Lovett, P. Meir, C. Mendoza, A. Morel, P. Nunez Vargas, S. Patino, K.S.H. Peh, A. Pena Cruz, A. Prieto, C.A. Quesada, F. Ramirez, H. Ramirez, A. Rudas, R. Salamao, M. Schwarz, J. Silva, M. Silveira, J.W.F. Slik, B. Sonke, A.S. Thomas, J. Stropp, J.R.D. Taplin, R. Vasquez, and E. Vilanova, 2010: Drought-mortality relationships for tropical forests. *New Phytologist*, **187(3)**, 631-646.

Pielke, R.A., A. Pitman, D. Niyogi, R. Mahmood, C. McAlpine, F. Hossain, K.K. Goldewijk, U. Nair, R. Betts, S. Fall, M. Reichstein, P. Kabat, and N. de Noblet, 2011: Land use/land cover changes and climate: modeling analysis and observational evidence. *Wiley Interdisciplinary Reviews: Climate Change*, **2(6)**, 828-850.

Pitman, A.J., G.T. Narisma, and J. McAneney, 2007: The impact of climate change on the risk of forest and grassland fires in Australia. *Climatic Change*, **84(3-4)**, 383-401.

Pitman, A.J., N. de Noblet-Ducoudre, F.T. Cruz, E.L. Davin, G.B. Bonan, V. Brovkin, M. Claussen, C. Delire, L. Ganzeveld, V. Gayler, B.J.J.M. van den Hurk, P.J. Lawrence, M.K. van der Molen, C. Muller, C.H. Reick, S.I. Seneviratne, B.J. Strengers, and A. Voldoire, 2009: Uncertainties in climate responses to past land cover change: first results from the LUCID intercomparison study. *Geophysical Research Letters*, **36(14),** L14814, doi:10.1029/2009GL039076.

Plevin, R.J., M. O'Hare, A.D. Jones, M.S. Torn, and H.K. Gibbs, 2010: Greenhouse gas emissions from biofuels' indirect land use change are uncertain but may be much greater than previously estimated. *Environmental Science & Technology*, **44(21)**, 8015-8021.

Poff, N.L., B.D. Richter, A.H. Arthington, S.E. Bunn, R.J. Naiman, E. Kendy, M. Acreman, C. Apse, B.P. Bledsoe, M.C. Freeman, J. Henriksen, R.B. Jacobson, J.G. Kennen, D.M. Merritt, J.H. O'Keeffe, J.D. Olden, K. Rogers, R.E. Tharme, and A. Warner, 2010: The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology*, **55(1)**, 147-170.

Polis, G.A., W.B. Anderson, and R.D. Holt, 1997: Toward an integration of landscape and food web ecology: the dynamics of spatially subsidized food webs. *Annual Review of Ecology and Systematics*, **28**, 289-316.

Ponniah, M. and J.M. Hughes, 2004: The evolution of Queensland spiny mountain crayfish of the genus Euastacus. I. Testing vicariance and dispersal with interspecific mitochondrial DNA. *Evolution*, **58(5)**, 1073-1085.

Porter, T.J. and M.F.J. Pisaric, 2011: Temperature-growth divergence in white spruce forests of Old Crow Flats, Yukon Territory, and adjacent regions of northwestern North America. *Global Change Biology*, **17(11)**, 3418-3430.

Post, E. and J. Brodie, 2012: Extinction risk at high latitudes. In: *Saving a Million Species: Extinction Risk From Climate Change* [Hannah, L. (ed.)]. Island Press, Washington, DC, USA, pp. 121-137.

Post, E., C. Pedersen, C.C. Wilmers, and M.C. Forchhammer, 2008: Warming, plant phenology and the spatial dimension of trophic mismatch for large herbivores. *Proceedings of the Royal Society B*, **275(1646)**, 2005-2013.

Post, E., M.C. Forchhammer, M.S. Bret-Harte, T.V. Callaghan, T.R. Christensen, B. Elberling, A.D. Fox, O. Gilg, D.S. Hik, T.T. Hoye, R.A. Ims, E. Jeppesen, D.R. Klein, J. Madsen, A.D. McGuire, S. Rysgaard, D.E. Schindler, I. Stirling, M.P. Tamstorf, N.J.C. Tyler, R. van der Wal, J. Welker, P.A. Wookey, N.M. Schmidt, and P. Aastrup, 2009: Ecological dynamics across the Arctic associated with recent climate change. *Science*, **325(5946)**, 1355-1358.

Potts, S.G., J.C. Biesmeijer, C. Kremen, P. Neumann, O. Schweiger, and W.E. Kunin, 2010: Global pollinator declines: trends, impacts and drivers. *Trends in Ecology & Evolution*, **25(6)**, 345-353.

Potvin, C., F. Chapin, A. Gonzalez, P. Leadley, P. Reich, and J. Roy, 2007: Plant biodiversity and responses to elevated carbon dioxide. In: *Terrestrial Ecosystems in a Changing World* [Canadell, J.G., D.E. Pataki, and L.F. Pitelka (eds.)]. Global Change – The IGBP Series, Springer-Verlag, Berlin, Heidelberg, Germany, pp. 103-112.

Pounds, J.A., M.R. Bustamante, L.A. Coloma, J.A. Consuegra, M.P.L. Fogden, P.N. Foster, E. La Marca, K.L. Masters, A. Merino-Viteri, R. Puschendorf, S.R. Ron, G.A. Sanchez-Azofeifa, C.J. Still, and B.E. Young, 2006: Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature*, **439(7073)**, 161-167.

Powell, T.L., D.R. Galbraith, B.O. Christoffersen, A. Harper, H.M.A. Imbuzeiro, L. Rowland, S. Almeida, P.M. Brando, A. Carlos Lola da Costa, M. Heil Costa, N.M. Levine, Y. Malhi, S.R. Saleska, E. Sotta, M. Williams, P. Meir, and P.R. Moorcroft, 2013: Confronting model predictions of carbon fluxes with measurements of Amazon forests subjected to experimental drought. *New Phytologist*, **200**, 350-364.

Power, S.A., E.R. Green, C.G. Barker, J.N.B. Bell, and M.R. Ashmore, 2006: Ecosystem recovery: heathland response to a reduction in nitrogen deposition. *Global Change Biology*, **12(7)**, 1241-1252.

Prentice, I.C. and S.P. Harrison, 2009: Ecosystem effects of CO_2 concentration: evidence from past climates. *Climate of the Past*, **5(3)**, 297-307.

Prentice, I.C., J. Guiot, B. Huntley, D. Jolly, and R. Cheddadi, 1996: Reconstructing biomes from palaeoecological data: a general method and its application to European pollen data at 0 and 6 ka. *Climate Dynamics*, **12**, 185-194.

Prentice, I.C., S.P. Harrison, and P.J. Bartlein, 2011: Global vegetation and terrestrial carbon cycle changes after the last ice age. *New Phytologist*, **189(4)**, 988-998.

Prieto, P., J. Penuelas, J. Llusia, D. Asensio, and M. Estiarte, 2009: Effects of long-term experimental night-time warming and drought on photosynthesis, Fv/Fm and stomatal conductance in the dominant species of a Mediterranean shrubland. *Acta Physiologiae Plantarum*, **31(4)**, 729-739.

Primack, R.B., I. Ibáñez, H. Higuchi, S.D. Lee, A.J. Miller-Rushing, A.M. Wilson, and J.A. Silander Jr., 2009: Spatial and interspecific variability in phenological responses to warming temperatures. *Biological Conservation*, **142(11)**, 2569-2577.

Prince, S.D., K.J. Wessels, C.J. Tucker, and S.E. Nicholson, 2007: Desertification in the Sahel: a reinterpretation of a reinterpretation. *Global Change Biology*, **13(7)**, 1308-1313.

Pringle, C.M., 2001: Hydrologic connectivity and the management of biological reserves: a global perspective. *Ecological Applications*, **11(4)**, 981-998.

Prost, S., R.P. Guralnick, E. Waltari, V.B. Fedorov, E. Kuzmina, N. Smirnov, T. Van Kolfschoten, M. Hofreiter, and K. Vrieling, 2013: Losing ground: past history and future fate of Arctic small mammals in a changing climate. *Global Change Biology*, **19(6)**, 1854-1864.

Prowse, T.D. and K. Brown, 2010: Hydro-ecological effects of changing Arctic river and lake ice covers: a review. *Hydrology Research*, **41(6)**, 454-461.

Prugh, L.R., K.E. Hodges, A.R.E. Sinclair, and J.S. Brashares, 2008: Effect of habitat area and isolation on fragmented animal populations. *Proceedings of the National Academy of Sciences of the United States of America*, **105(52)**, 20770-20775.

Pulido, F., 2007: Phenotypic changes in spring arrival: evolution, phenotypic plasticity, effects of weather and condition. *Climate Research*, **35(1-2)**, 5-23.

Racine, C., R. Jandt, C. Meyers, and J. Dennis, 2004: Tundra fire and vegetation change along a hillslope on the Seward Peninsula, Alaska, U.S.A. *Arctic*, *Antarctic*, *and Alpine Research*, **36(1)**, 1-10.

Raffa, K.F., B.H. Aukema, B.J. Bentz, A.L. Carroll, J.A. Hicke, M.G. Turner, and W.H. Romme, 2008: Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. *BioScience*, **58(6)**, 501-517.

Raghu, S., R.C. Anderson, C.C. Daehler, A.S. Davis, R.N. Wiedenmann, D. Simberloff, and R.N. Mack, 2006: Adding biofuels to the invasive species fire? *Science*, **313(5794)**, 1742-1742.

Rahel, F.J. and J.D. Olden, 2008: Assessing the effects of climate change on aquatic invasive species. *Conservation Biology*, **22(3)**, 521-533.

Randerson, J.T., H. Liu, M.G. Flanner, S.D. Chambers, Y. Jin, P.G. Hess, G. Pfister, M.C. Mack, K.K. Treseder, L.R. Welp, F.S. Chapin, J.W. Harden, M.L. Goulden, E. Lyons, J.C. Neff, E.A.G. Schuur, and C.S. Zender, 2006: The impact of boreal forest fire on climate warming. *Science*, **314(5802)**, 1130-1132.

Randin, C.F., R. Engler, S. Normand, M. Zappa, N.E. Zimmermann, P.B. Pearman, P. Vittoz, W. Thuiller, and A. Guisan, 2009: Climate change and plant distribution: local models predict high-elevation persistence. *Global Change Biology*, **15(6)**, 1557-1569.

Raupach, M.R., J.G. Canadell, and C. Le Quéré, 2008: Anthropogenic and biophysical contributions to increasing atmospheric CO_2 growth rate and airborne fraction. *Biogeosciences*, **5(6)**, 1601-1613.

Ravi, S., D.D. Breshears, T.E. Huxman, and P. D'Odorico, 2010: Land degradation in drylands: interactions among hydrologic-aeolian erosion and vegetation dynamics. *Geomorphology*, **116(3-4)**, 236-245.

Rawson, D.M., G.M. Reid, and R.E. Lloyd, 2011: Conservation rationale, research applications and techniques in the cryopreservation of lower vertebrate biodiversity from marine and freshwater environments. *International Zoo Yearbook*, **45**, 108-123.

Raxworthy, C.J., R.G. Pearson, N. Rabibisoa, A.M. Rakotondrazafy, J.B. Ramanamanjato, A.P. Raselimanana, S. Wu, R.A. Nussbaum, and D.A. Stone, 2008: Extinction vulnerability of tropical montane endemism from warming and upslope displacement: a preliminary appraisal for the highest massif in Madagascar. *Global Change Biology*, **14(8)**, 1703-1720.

Ray, D., D. Nepstad, and P. Moutinho, 2005: Micrometeorological and canopy controls of flammability in mature and disturbed forests in an east-central Amazon landscape. *Ecological Applications*, **15(5)**, 1664-1678.

Ray, D.K., N. Ramankutty, N.D. Mueller, P.C. West, and J.A. Foley, 2012: Recent patterns of crop yield growth and stagnation. *Nature Communications*, **3**, 1293, doi:10.1038/ncomms2296.

Réale, D., A.G. McAdam, S. Boutin, and D. Berteaux, 2003: Genetic and plastic responses of a northern mammal to climate change. *Proceedings of the Royal Society B*, **270(1515)**, 591-596.

Reed, T.E., V. Grotan, S. Jenouvrier, B.E. Saether, and M.E. Visser, 2013: Population growth in a wild bird is buffered against phenological mismatch. *Science*, **340(6131)**, 488-491.

Regnier, C., B. Fontaine, and P. Bouchet, 2009: Not knowing, not recording, not listing: numerous unnoticed mollusk extinctions. *Conservation Biology*, **23(5)**, 1214-1221.

Rehfeldt, G.E. and B.C. Jaquish, 2010: Ecological impacts and management strategies for western larch in the face of climate-change. *Mitigation and Adaptation Strategies for Global Change*, **15(3)**, 283-306.

Rehfeldt, G.E., N.L. Crookston, C. Saenz-Romero, and E.M. Campbell, 2012: North American vegetation model for land-use planning in a changing climate: a solution to large classification problems. *Ecological Applications*, **22(1)**, 119-141.

Reich, P.B., 2009: Elevated CO_2 reduces losses of plant diversity caused by nitrogen deposition. *Science*, **326(5958)**, 1399-1402.

Reich, P.B., S.E. Hobbie, T. Lee, D.S. Ellsworth, J.B. West, D. Tilman, J.M.H. Knops, S. Naeem, and J. Trost, 2006: Nitrogen limitation constrains sustainability of ecosystem response to CO_2. *Nature*, **440(7086)**, 922-925.

Reidy Liermann, C., C. Nilsson, J. Robertson, and R.Y. Ng, 2012: Implications of dam obstruction for global freshwater fish diversity. *BioScience*, **62(6)**, 539-548.

Reist, J.D., F.J. Wrona, T.D. Prowse, M. Power, J.B. Dempson, R.J. Beamish, J.R. King, T.J. Carmichael, and C.D. Sawatzky, 2006: General effects of climate change on Arctic fishes and fish populations. *Ambio*, **35(7)**, 370-380.

Renwick, A.R., D. Massimino, S.E. Newson, D.E. Chamberlain, J.W. Pearce-Higgins, and A. Johnston, 2012: Modelling changes in species' abundance in response to projected climate change. *Diversity and Distributions*, **18(2)**, 121-132.

Riahi, K., S. Rao, V. Krey, C. Cho, V. Chirkov, G. Fischer, G. Kindermann, N. Nakicenovic, and P. Rafaj, 2011: RCP 8.5 – a scenrio of comparatively high greenhouse gas emissions. *Climatic Change*, **109**, 33-57.

Ricciardi, A. and D. Simberloff, 2009: Assisted colonization is not a viable conservation strategy. *Trends in Ecology & Evolution*, **24(5)**, 248-253.

Richardson, D.M., J.J. Hellmann, J.S. McLachlan, D.F. Sax, M.W. Schwartz, P. Gonzalez, E.J. Brennan, A. Camacho, T.L. Root, O.E. Sala, S.H. Schneider, D.M. Ashe, J.R. Clark, R. Early, J.R. Etterson, E.D. Fielder, J.L. Gill, B.A. Minteer, S. Polasky, H.D. Safford, A.R. Thompson, and M. Vellend, 2009: Multidimensional evaluation of managed relocation. *Proceedings of the National Academy of Sciences of the United States of America*, **106(24)**, 9721-9724.

Ridgwell, A., J.S. Singarayer, A.M. Hetherington, and P.J. Valdes, 2009: Tackling regional climate change by leaf albedo bio-geoengineering. *Current Biology*, **19(2)**, 146-150.

Rieley, J.O., R.A.J. Wüst, J. Jauhiainen, S.E. Page, J.H.M. Wösten, A. Hooijer, E. Siegert, S.H. Limin, H. Vasander, and M. Stahlhut, 2008: Tropical peatlands: carbon stores, carbon gas emissions and contribution to climate change processes. In: *Peatlands and Climate Change* [Strack, M. (ed.)]. International Peat Society, Jyväskylä, Finland, pp. 148-181.

Roberts, S.P.M., S.G. Potts, J. Biesmeijer, M. Kuhlmann, B. Kunin, and R. Ohlemüller, 2011: Assessing continental-scale risks for generalist and specialist pollinating bee species under climate change. *BioRisk*, **6**, 1-18.

Robinet, C. and A. Roques, 2010: Direct impacts of recent climate warming on insect populations. *Integrative Zoology*, **5(2)**, 132-142.

Rocha, A.V. and G.R. Shaver, 2011: Burn severity influences postfire CO_2 exchange in arctic tundra. *Ecological Applications*, **21(2)**, 477-489.

Rodriguez-Labajos, B., 2013: Climate and change, ecosystems services and costs of action and inaction: scoping the interface. *Wiley Interdisciplinary Review: Climate Change*, **4(6)**, 555-573.

Rohde, R.F. and M.T. Hoffman, 2012: The historical ecology of Namibian rangelands: Vegetation change since 1876 in response to local and global drivers. *Science of the Total Environment*, **416**, 276-288.

Roland, C.A., J.H. Schmidt, and E.F. Nicklen, 2013: Landscape-scale patterns in tree occupancy and abundance in subarctic Alaska. *Ecological Monographs*, **83(1)**, 19-48.

Romanovsky, V.E., S.L. Smith, and H.H. Christiansen, 2010: Permafrost thermal state in the polar Northern Hemisphere during the International Polar Year 2007-2009: a synthesis. *Permafrost and Periglacial Processes*, **21(2)**, 106-116.

Romijn, E., M. Herold, L. Kooistra, D. Murdiyarso, and L. Verchot, 2012: Assessing capacities of non-Annex I countries for national forest monitoring in the context of REDD+. *Environmental Science and Policy*, **19-20**, 33-48.

Root, T.L., J.T. Price, K.R. Hall, S.H. Schneider, C. Rosenzweig, and J.A. Pounds, 2003: Fingerprints of global warming on wild animals and plants. *Nature*, **421(6918)**, 57-60.

Rosenheim, J.A. and B.E. Tabashnik, 1991: Influence of generation time on the response to selection. *American Naturalist*, **137(4)**, 527-541.

Rosenzweig, C., G. Casassa, D.J. Karoly, A. Imeson, C. Liu, A. Menzel, S. Rawlins, T.L. Root, B. Seguin, and P. Tryjanowski, 2007: Assessment of observed changes and responses in natural and managed systems. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 79-131.

Rosset, V., A. Lehmann, and B. Oertli, 2010: Warmer and richer? Predicting the impact of climate warming on species richness in small temperate waterbodies. *Global Change Biology*, **16(8)**, 2376-2387.

Rössler, M., 2006: World heritage cultural landscapes: a UNESCO flagship programme 1992-2006. *Landscape Research*, **31(4)**, 333-353.

Rounsevell, M.D.A. and D.S. Reay, 2009: Land use and climate change in the UK. *Land Use Policy*, **26(Suppl 1)**, S160-S169.

Roux, D.J., J.L. Nel, P.J. Ashton, A.R. Deaconc, F.C. de Moor, D. Hardwick, L. Hill, C.J. Kleynhans, G.A. Maree, J. Moolman, and R.J. Scholes, 2008: Designing protected areas to conserve riverine biodiversity: lessons from a hypothetical redesign of the Kruger National Park. *Biological Conservation*, **141(1)**, 100-117.

Rowe, R.J., J.A. Finarelli, and E.A. Rickart, 2010: Range dynamics of small mammals along an elevational gradient over an 80-year interval. *Global Change Biology*, **16(11)**, 2930-2943.

Rubidge, E.M., W.B. Monahan, J.L. Parra, S.E. Cameron, and J.S. Brashares, 2011: The role of climate, habitat, and species co-occurrence as drivers of change in small mammal distributions over the past century. *Global Change Biology*, **17(2)**, 696-708.

Ruiz-Labourdette, D., M.F. Schmitz, and F.D. Pineda, 2013: Changes in tree species composition in Mediterranean mountains under climate change: indicators for conservation planning. *Ecological Indicators*, **24**, 310-323.

Rupp, T.S., F.S. Chapin, and A. Starfield, 2001: Modeling the influence of topographic barriers on treeline advance at the forest-tundra ecotone in northwestern Alaska. *Climatic Change*, **48(2)**, 399-416.

Russell, L.M., P.J. Rasch, G.M. Mace, R.B. Jackson, J. Shepherd, P. Liss, M. Leinen, D. Schimel, N.E. Vaughan, A.C. Janetos, P.W. Boyd, R.J. Norby, K. Caldeira, J. Merikanto, P. Artaxo, J. Melillo, and M.G. Morgan, 2012: Ecosystem impacts of geoengineering: a review for developing a science plan. *Ambio*, **41(4)**, 350-369.

Rustad, L.E., 2008: The response of terrestrial ecosystems to global climate change: towards an integrated approach. *Science of the Total Environment*, **404(2-3)**, 222-235.

Ryan, M.G., M.E. Harmon, R.A. Birdsey, C.P. Giardina, L.S. Heath, R.A. Houghton, R.B. Jackson, D.C. McKinley, J.F. Morrison, B.C. Murray, D.E. Pataki, and K.E. Skog, 2010: A synthesis of the science on forests and carbon for U.S. forests. *Issues in Ecology*, **13**, 1-16.

Saatchi, S., S. Asefi-Najafabady, Y. Malhi, L.E.O.C. Aragão, L.O. Anderson, R.B. Myneni, and R. Nemani, 2013: Persistent effects of a severe drought on Amazonian forest canopy. *Proceedings of the National Academy of Sciences of the United States of America*, **110(2)**, 565-570.

Saino, N., D. Rubolini, E. Lehikoinen, L.V. Sokolov, A. Bonisoli-Alquati, R. Ambrosini, G. Boncoraglio, and A.P. Moller, 2009: Climate change effects on migration phenology may mismatch brood parasitic cuckoos and their hosts. *Biology Letters*, **5(4)**, 539-541.

Sala, O.E., W.J. Parton, L.A. Joyce, and W.K. Lauenroth, 1988: Primary production of the Central Grassland Region of the United States. *Ecology*, **69(1)**, 10-45.

Salamin, N., R.O. Wuest, S. Lavergne, W. Thuiller, and P.B. Pearman, 2010: Assessing rapid evolution in a changing environment. *Trends in Ecology & Evolution*, **25(12)**, 692-698.

Salzmann, U., A.M. Haywood, D.J. Lunt, P.J. Valdes, and D.J. Hill, 2008: A new global biome reconstruction and data-model comparison for the Middle Pliocene. *Global Ecology and Biogeography*, **17(3)**, 432-447.

Samanta, A., M.H. Costa, E.L. Nunes, S.A. Vieira, L. Xu, and R.B. Myneni, 2011: Comment on "Drought-induced reduction in global terrestrial net primary production from 2000 through 2009". *Science*, **333(6046)**, 1093-c.

Sandel, B. and E.M. Dangremond, 2012: Climate change and the invasion of California by grasses. *Global Change Biology*, **18(1)**, 277-289.

Sandel, B., L. Arge, B. Dalsgaard, R.G. Davies, K.J. Gaston, W.J. Sutherland, and J.C. Svenning, 2011: The influence of Late Quaternary climate-change velocity on species endemism. *Science*, **334(6056)**, 660-664.

Sankaran, M., N.P. Hanan, R.J. Scholes, J. Ratnam, D.J. Augustine, B.S. Cade, J. Gignoux, S.I. Higgins, X. Le Roux, F. Ludwig, J. Ardo, F. Banyikwa, A. Bronn, G. Bucini, K.K. Caylor, M.B. Coughenour, A. Diouf, W. Ekaya, C.J. Feral, E.C. February, P.G.H. Frost, P. Hiernaux, H. Hrabar, K.L. Metzger, H.H.T. Prins, S. Ringrose, W. Sea, J. Tews, J. Worden, and N. Zambatis, 2005: Determinants of woody cover in African savannas. *Nature*, **438(7069)**, 846-849.

Santini, L., M. Di Marco, P. Visconti, D. Baisero, L. Boitani, and C. Rondinini, 2013: Ecological correlates of dispersal distance in terrestrial mammals. *Hystrix*, *the Italian Journal of Mammalogy*, **24(2)**, doi:10.4404/hystrix-24.2-8746.

Saraux, C., C. Le Bohec, J.M. Durant, V.A. Viblanc, M. Gauthier-Clerc, D. Beaune, Y.-H. Park, N.G. Yoccoz, N.C. Stenseth, and Y. Le Maho, 2011: Reliability of flipper-banded penguins as indicators of climate change. *Nature*, **469(7329)**, 203-206.

Sardans, J., J. Penuelas, M. Estiarte, and P. Prieto, 2008a: Warming and drought alter C and N concentration, allocation and accumulation in a Mediterranean shrubland. *Global Change Biology*, **14(10)**, 2304-2316.

Sardans, J., J. Penuelas, P. Prieto, and M. Estiarte, 2008b: Changes in Ca, Fe, Mg, Mo, Na, and S content in a Mediterranean shrubland under warming and drought. *Journal of Geophysical Research: Biogeosciences*, **113(G3)**, G03039, doi:10.1029/2008JG000795.

Sardans, J., A. Rivas-Ubach, and J. Penuelas, 2012: The C:N:P stoichiometry of organisms and ecosystems in a changing world: a review and perspectives. *Perspectives in Plant Ecology Evolution and Systematics*, **14(1)**, 33-47.

Sarris, D., D. Christodoulakis, and C. Körner, 2011: Impact of recent climatic change on growth of low elevation eastern Mediterranean forest trees. *Climatic Change*, **106(2)**, 203-223.

Sato, H. and T. Ise, 2012: Effect of plant dynamic processes on African vegetation responses to climate change: analysis using the spatially explicit individual-based dynamic global vegetation model (SEIB-DGVM). *Journal of Geophysical Research: Biogeosciences*, **117(G3)**, G03017, doi:10.1029/2012JG002056.

Sauer, J., S. Domisch, C. Nowak, and P. Haase, 2011: Low mountain ranges: summit traps for montane freshwater species under climate change. *Biodiversity and Conservation*, **20(13)**, 3133-3146.

Saurral, R.I., V.R. Barros, and D.P. Lettenmaier, 2008: Land use impact on the Uruguay River discharge. *Geophysical Research Letters*, **35(12)**, L12401.

Schaefer, K., T.J. Zhang, L. Bruhwiler, and A.P. Barrett, 2011: Amount and timing of permafrost carbon release in response to climate warming. *Tellus Series B: Chemical and Physical Meteorology*, **63(2)**, 165-180.

Schaper, S.V., A. Dawson, P.J. Sharp, P. Gienapp, S.P. Caro, and M.E. Visser, 2012: Increasing temperature, not mean temperature, is a cue for avian timing of reproduction. *The American Naturalist*, **179(2)**, E55-E69.

Scheffer, M., 2009: *Critical Transitions in Nature and Society*. Princeton University Press, Princeton, NJ, USA, 400 pp.

Scheffer, M., J. Bascompte, W.A. Brock, V. Brovkin, S.R. Carpenter, V. Dakos, H. Held, E.H. van Nes, M. Rietkerk, and G. Sugihara, 2009: Early-warning signals for critical transitions. *Nature*, **461(7260)**, 53-59.

Scheffer, M., M. Hirota, M. Holmgren, E.H. Van Nes, and F.S. Chapin III, 2012: Thresholds for boreal biome transitions. *Proceedings of the National Academy of Sciences of the United States of America*, **109(52)**, 21384-21389.

Scheiter, S. and S.I. Higgins, 2009: Impacts of climate change on the vegetation of Africa: an adaptive dynamic vegetation modelling approach. *Global Change Biology*, **15(9)**, 2224-2246.

Schiffers, K., E.C. Bourne, S. Lavergne, W. Thuiller, and J.M.J. Travis, 2013: Limited evolutionary rescue of locally adapted populations facing climate change. *Philosophical Transactions of the Royal Society B*, **368(1610)**, 20120083, doi:10.1098/rstb.2012.0083.

Schippers, P., J. Verboom, C.C. Vos, and R. Jochem, 2011: Metapopulation shift and survival of woodland birds under climate change: will species be able to track? *Ecography*, **34(6)**, 909-919.

Schloss, C.A., T.A. Nunez, and J.J. Lawler, 2012: Dispersal will limit ability of mammals to track climate change in the Western Hemisphere. *Proceedings of the National Academy of Sciences of the United States of America*, **109(22)**, 8606-8611.

Schneider, A., M.A. Friedl, and D. Potere, 2009: A new map of global urban extent from MODIS satellite data. *Environmental Research Letters*, **4(4)**, 044003, doi:10.1088/1748-9326/4/4/044003.

Schneider, C., 2003: The influence of spatial scale on quantifying insect dispersal: an analysis of butterfly data. *Ecological Entomology*, **28(2)**, 252-256.

Schnitzler, A., B.W. Hale, and E.M. Alsum, 2007: Examining native and exotic species diversity in European riparian forests. *Biological Conservation*, **138(1-2)**, 146-156.

Scholes, R.J. and S.R. Archer, 1997: Tree-grass interactions in savannas. *Annual Review of Ecology and Systematics*, **28**, 517-544.

Scholze, M., W. Knorr, N.W. Arnell, and I.C. Prentice, 2006: A climate-change risk analysis for world ecosystems. *Proceedings of the National Academy of Sciences of the United States of America*, **103(35)**, 13116-13120.

Schulte, P., L. Alegret, I. Arenillas, J.A. Arz, P.J. Barton, P.R. Bown, T.J. Bralower, G.L. Christeson, P. Claeys, C.S. Cockell, G.S. Collins, A. Deutsch, T.J. Goldin, K. Goto, J.M. Grajales-Nishimura, R.A.F. Grieve, S.P.S. Gulick, K.R. Johnson, W. Kiessling, C. Koeberl, D.A. Kring, K.G. MacLeod, T. Matsui, J. Melosh, A. Montanari, J.V. Morgan, C.R. Neal, D.J. Nichols, R.D. Norris, E. Pierazzo, G. Ravizza, M. Rebolledo-Vieyra, W.U. Reimold, E. Robin, T. Salge, R.P. Speijer, A.R. Sweet, J. Urrutia-Fucugauchi, V. Vajda, M.T. Whalen, and P.S. Willumsen, 2010: The Chicxulub Asteroid impact and mass extinction at the Cretaceous-Paleogene Boundary. *Science*, **327(5970)**, 1214-1218.

Schultz, M.G., A. Heil, J.J. Hoelzemann, A. Spessa, K. Thonicke, J.G. Goldammer, A.C. Held, J.M.C. Pereira, and M. van het Bolscher, 2008: Global wildland fire emissions from 1960 to 2000. *Global Biogeochemical Cycles*, **22(2)**, GB2002, doi:10.1029/2007GB003031.

Schuur, E.A.G., J. Bockheim, J.G. Canadell, E. Euskirchen, C.B. Field, S.V. Goryachkin, S. Hagemann, P. Kuhry, P.M. Lafleur, H. Lee, G. Mazhitova, F.E. Nelson, A. Rinke, V.E. Romanovsky, N. Shiklomanov, C. Tarnocai, S. Venevsky, J.G. Vogel, and S.A. Zimov, 2008: Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle. *BioScience*, **58(8)**, 701-714.

Schuur, E.A.G., J.G. Vogel, K.G. Crummer, H. Lee, J.O. Sickman, and T.E. Osterkamp, 2009: The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. *Nature*, **459(7246)**, 556-559.

Schuur, E.A.G., B.W. Abbott, W.B. Bowden, V. Brovkin, P. Camill, J.G. Canadell, J.P. Chanton, F.S. Chapin III, T.R. Christensen, P. Ciais, B.T. Crosby, C.I. Czimczik, G. Grosse, J. Harden, D.J. Hayes, G. Hugelius, J.D. Jastrow, J.B. Jones, T. Kleinen, C.D. Koven, G. Krinner, P. Kuhry, D.M. Lawrence, A.D. McGuire, S.M. Natali, J.A. O'Donnell, C.L. Ping, W.J. Riley, A. Rinke, V.E. Romanovsky, A.B.K. Sannel, C. Schädel, K. Schaefer, J. Sky, Z.M. Subin, C. Tarnocai, M.R. Turetsky, M.P. Waldrop, K.M. Walter Anthony, K.P. Wickland, C.J. Wilson, and S.A. Zimov, 2013: Expert assessment of vulnerability of permafrost carbon to climate change. *Climate Change*, **119**, 359–374. doi:10.1007/s10584-013-0730-7.

Schwaiger, H.P. and D.N. Bird, 2010: Integration of albedo effects caused by land use change into the climate balance: should we still account in greenhouse gas units? *Forest Ecology and Management*, **260(3)**, 278-286.

Schweiger, O., J. Settele, O. Kudrna, S. Klotz, and I. Kühn, 2008: Climate change can cause spatial mismatch of trophically interacting species. *Ecology*, **89(12)**, 3472-3479.

Schweiger, O., J.C. Biesmeijer, R. Bommarco, T. Hickler, P.E. Hulme, S. Klotz, I. Kuehn, M. Moora, A. Nielsen, R. Ohlemüller, T. Petanidou, S.G. Potts, P. Pyšek, J.C. Stout, M.T. Sykes, T. Tscheulin, M. Vila, G.-R. Walther, C. Westphal, M. Winter, M. Zobel, and J. Settele, 2010: Multiple stressors on biotic interactions: how climate change and alien species interact to affect pollination. *Biological Reviews*, **85(4)**, 777-795.

Schweiger, O., A. Harpke, R. Heikkinen, T. Hickler, I. Kühn, J. Pöyry, and J. Settele, 2012: Increasing range mismatching of interacting species under global change is related to their ecological characteristics. *Global Ecology and Biogeography*, **21(1)**, 88-99.

Seaquist, J.W., T. Hickler, L. Eklundh, J. Ardö, and B.W. Heumann, 2009: Disentangling the effects of climate and people on Sahel vegetation dynamics. *Biogeosciences*, **6(3)**, 469-477.

Searchinger, T., R. Heimlich, R.A. Houghton, F.X. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.H. Yu, 2008: Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, **319(5867)**, 1238-1240.

Seidel, D.J., Q. Fu, W.J. Randel, and T.J. Reichler, 2008: Widening of the tropical belt in a changing climate. *Nature Geoscience*, **1(1)**, 21-24.

Sekercioglu, C.H., R.B. Primack, and J. Wormworth, 2012: The effects of climate change on tropical birds. *Biological Conservation*, **148(1)**, 1-18.

Selsted, M.B., L. van der Linden, A. Ibrom, A. Michelsen, K.S. Larsen, J.K. Pedersen, T.N. Mikkelsen, K. Pilegaard, C. Beier, and P. Ambus, 2012: Soil respiration is stimulated by elevated CO_2 and reduced by summer drought: three years of measurements in a multifactor ecosystem manipulation experiment in a temperate heathland (CLIMAITE). *Global Change Biology*, **18(4)**, 1216-1230.

Seppälä, R., 2009: A global assessment on adaptation of forests to climate change. *Scandinavian Journal of Forest Research*, **24(6)**, 469-472.

Seppelt, R., C.F. Dormann, F.V. Eppink, S. Lautenbach, and S. Schmidt, 2011: A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead. *Journal of Applied Ecology*, **48(3)**, 630-636.

Serreze, M.C. and J.A. Francis, 2006: The Arctic amplification debate. *Climate Change*, **76(3)**, 241-264.

Settele, J. and E. Kühn, 2009: Insect conservation. *Science*, **325(5936)**, 41-42.

Settele, J., O. Kudrna, A. Harpke, I. Kühn, C. Van Swaay, R. Verovnik, M. Warren, M. Wiemers, J. Hanspach, T. Hickler, E. Kühn, I. Van Halder, K. Veling, A. Vliegenthart, I. Wynhoff, and O. Schweiger, 2008: Special Issue: Climatic Risk Atlas of European Butterflies. *BioRisk*, **1**, 1-710, doi:10.3897/biorisk.1.

Settele, J., L. Penev, T. Georgiev, R. Grabaum, V. Grobelnik, V. Hammen, S. Klotz, M. Kotarac, and I. Kühn (eds.), 2010a: *Atlas of Biodiversity Risk*. Pensoft Publishers, Sofia, Bulgaria, 300 pp.

Settele, J., M. Zobel, J.H. Spangenberg, S. Klotz, V. Hammen, and I. Kühn, 2010b: Designing projects for integrated research – the ALARM experience. In: *Atlas of Biodiversity Risk* [Settele, J., L. Penev, T. Georgiev, R. Grabaum, V. Grobelnik, V. Hammen, S. Klotz, M. Kotarac, and I. Kühn (eds.)]. Pensoft Publishers, Sofia, Bulgaria, pp. 208-209.

Shakesby, R.A., 2011: Post-wildfire soil erosion in the Mediterranean: review and future research directions. *Earth-Science Reviews*, **105(3-4)**, 71-100.

Shanin, V.N., A.S. Komarov, A.V. Mikhailov, and S.S. Bykhovets, 2011: Modelling carbon and nitrogen dynamics in forest ecosystems of Central Russia under different climate change scenarios and forest management regimes. *Ecological Modelling*, **222(14)**, 2262-2275.

Sharma, S., S. Couturier, and S.D. Cote, 2009: Impacts of climate change on the seasonal distribution of migratory caribou. *Global Change Biology*, **15(10)**, 2549-2562.

Sharp, B.R. and D.M.J.S. Bowman, 2004: Patterns of long-term woody vegetation change in a sandstone-plateau savanna woodland, Northern Territory, Australia. *Journal of Tropical Ecology*, **20(03)**, 259-270.

Shaw, M.R., E.S. Zavaleta, N.R. Chiariello, E.E. Cleland, H.A. Mooney, and C.B. Field, 2002: Grassland responses to global environmental changes suppressed by elevated CO_2. *Science*, **298(5600)**, 1987-1990.

Sheldon, F., S.E. Bunn, J.M. Hughes, A.H. Arthington, S.R. Balcombe, and C.S. Fellows, 2010: Ecological roles and threats to aquatic refugia in arid landscapes: dryland river waterholes. *Marine and Freshwater Research*, **61(8)**, 885-895.

Shimazaki, M., I. Tsuyama, E. Nakazono, K. Nakao, M. Konoshima, N. Tanaka, and T. Nakashizuka, 2012: Fine-resolution assessment of potential refugia for a dominant fir species (*Abies mariesii*) of subalpine coniferous forests after climate change. *Plant Ecology*, **213(4)**, 603-612.

Shimoda, Y., M.E. Azim, G. Perhar, M. Ramin, M.A. Kenney, S. Sadraddini, A. Gudimov, and G.B. Arhonditsis, 2011: Our current understanding of lake ecosystem response to climate change: what have we really learned from the north temperate deep lakes? *Journal of Great Lakes Research*, **37(1)**, 173-193.

Shinoda, M., G.U. Nachinshonhor, and M. Nemoto, 2010: Impact of drought on vegetation dynamics of the Mongolian steppe: a field experiment. *Journal of Arid Environments*, **74(1)**, 63-69.

Shiogama, H., S. Emori, N. Hanasaki, M. Abe, Y. Masutomi, K. Takahashi, and T. Nozawa, 2011: Observational constraints indicate risk of drying in the Amazon basin. *Nature Communications*, **2**, 253, doi:10.1038/ncomms1252.

Silva, L.C.R. and M. Anand, 2013: Probing for the influence of atmospheric CO_2 and climate change on forest ecosystems across biomes. *Global Ecology and Biogeography*, **22(1)**, 83-92.

Silva, L.C.R., M. Anand, and M.D. Leithead, 2010: Recent widespread tree growth decline despite increasing atmospheric CO_2. *PLoS One*, **5(7)**, e11543, doi:10.1371/journal.pone.0011543.

Silvestrini, R., B. Soares-Filho, D. Nepstad, M.T. Coe, H. Rodrigues, and R. Assuncao, 2011: Simulating fire regimes in the Amazon in response to climate change and deforestation. *Ecological Applications*, **21(5)**, 1573-1590.

Simberloff, D., J.-L. Martin, P. Genovesi, V. Maris, D.A. Wardle, J. Aronson, F. Courchamp, B. Galil, E. García-Berthou, M. Pascal, P. Pyšek, R. Sousa, E. Tabacchi, and M. Vilà, 2013: Impacts of biological invasions: what's what and the way forward. *Trends in Ecology & Evolution*, **28(1)**, 58-66.

Sinervo, B., F. Mendez-de-la-Cruz, D.B. Miles, B. Heulin, E. Bastiaans, M.V.S. Cruz, R. Lara-Resendiz, N. Martinez-Mendez, M.L. Calderon-Espinosa, R.N. Meza-Lazaro, H. Gadsden, L.J. Avila, M. Morando, I.J. De la Riva, P.V. Sepulveda, C.F.D. Rocha, N. Ibarguengoytia, C.A. Puntriano, M. Massot, V. Lepetz, T.A. Oksanen, D.G. Chapple, A.M. Bauer, W.R. Branch, J. Clobert, and J.W. Sites, 2010: Erosion of lizard diversity by climate change and altered thermal niches. *Science*, **328(5980)**, 894-899.

Singer, M.C. and C. Parmesan, 2010: Phenological asynchrony between herbivorous insects and their hosts: signal of climate change or pre-existing adaptive strategy? *Philosophical Transactions of the Royal Society B*, **365(1555)**, 3161-3176.

Singh, A., S. Unnikrishnan, N. Naik, and K. Duvvuri, 2013: Role of India´s forest in climate change mitigation through the CDM and REDD+. *Journal of Environmental Planning and Management*, **56**, 61-87.

Sitch, S., P.M. Cox, W.J. Collins, and C. Huntingford, 2007: Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. *Nature*, **448(7155)**, 791-794.

Sitch, S., C. Huntingford, N. Gedney, P.E. Levy, M. Lomas, S.L. Piao, R. Betts, P. Ciais, P. Cox, P. Friedlingstein, C.D. Jones, I.C. Prentice, and F.I. Woodward, 2008: Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs). *Global Change Biology*, **14(9)**, 2015-2039.

Smallwood, K.S., 2007: Estimating wind turbine-caused bird mortality. *Journal of Wildlife Management*, **71(8)**, 2781-2791.

Smit, B., I. Burton, R.J.T. Klein, and J. Wandel, 2000: An anatomy of adaptation to climate change and variability. *Climatic Change*, **45(1)**, 223-251.

Smit, B., O. Pilifosova, I. Burton, B. Challenger, S. Huq, R.J.T. Klein, G. Yohe, N. Adger, T. Downing, E. Harvey, S. Kane, M. Parry, M. Skinner, J. Smith, and J. Wandel, 2007: Adaptation to climate change in the context of sustainable development and equity. In: *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 879-912.

Smith, A.L., N. Hewitt, N. Klenk, D.R. Bazely, N. Yan, S. Wood, I. Henriques, J.I. MacLellan, and C. Lipsig-Mummé, 2012: Effects of climate change on the distribution of invasive alien species in Canada: a knowledge synthesis of range change projections in a warming world. *Environmental Reviews*, **20(1)**, doi:10.1139/a11-020.

Smith, L.C., Y. Sheng, G.M. MacDonald, and L.D. Hinzman, 2005: Disappearing Arctic lakes. *Science*, **308(5727)**, 1429-1429.

Smith, S.J. and T.M.L. Wigley, 2006: Multi-gas forcing stabilization with minicam. *The Energy Journal*, **27 (SI3)**, 373-391.

Smol, J.P. and M.S.V. Douglas, 2007a: From controversy to consensus: making the case for recent climate using lake sediments. *Frontiers in Ecology and the Environment*, **5(9)**, 466-474.

Smol, J.P. and M.S.V. Douglas, 2007b: Crossing the final ecological threshold in high Arctic ponds. *Proceedings of the National Academy of Sciences of the United States of America*, **104(30)**, 12395-12397.

Snyman, H.A. and H.J. Fouché, 1993: Estimating seasonal herbage production of a semi-arid grassland based on veld condition, rainfall, and evapotranspiration. *African Journal of Range and Forage Science*, **10(1)**, 21-24.

Soares-Filho, B., P. Moutinho, D. Nepstad, A. Anderson, H. Rodrigues, R. Garcia, L. Dietzsch, F. Merry, M. Bowman, L. Hissa, R. Silvestrini, and C. Maretti, 2010: Role of Brazilian Amazon protected areas in climate change mitigation. *Proceedings of the National Academy of Sciences of the United States of America*, **107(24)**, 10821-10826.

Soares-Filho, B., R. Silvestrini, D. Nepstad, P. Brando, H. Rodrigues, A. Alencar, M. Coe, C. Locks, L. Lima, L. Hissa, and C. Stickler, 2012: Forest fragmentation, climate change and understory fire regimes on the Amazonian landscapes of the Xingu headwaters. *Landscape Ecology*, **27(4)**, 585-598.

Sobek-Swant, S., J.C. Crosthwaite, D.B. Lyons, and B.J. Sinclair, 2012: Could phenotypic plasticity limit an invasive species? Incomplete reversibility of mid-winter deacclimation in emerald ash borer. *Biological Invasions*, **14(1)**, 115-125.

Sodhi, N.S., D. Bickford, A.C. Diesmos, T.M. Lee, L.P. Koh, B.W. Brook, C.H. Sekercioglu, and C.J.A. Bradshaw, 2008: Measuring the meltdown: drivers of global amphibian extinction and decline. *PLoS One*, **3(2)**, e1636, doi:10.1371/journal.pone.0001636.

Soja, A.J., N.M. Tchebakova, N.H.F. French, M.D. Flannigan, H.H. Shugart, B.J. Stocks, A.I. Sukhinin, E.I. Parfenova, F.S. Chapin, and P.W. Stackhouse, 2007: Climate-induced boreal forest change: predictions versus current observations. *Global and Planetary Change*, **56(3-4)**, 274-296.

Sokolov, L., 2006: Effect of global warming on the timing of migration and breeding of passerine birds in the 20th century. *Entomological Review Supplement*, **86(1)**, S59-S81.

Soliani, C., L. Gallo, and P. Marchelli, 2012: Phylogeography of two hybridizing southern beeches (*Nothofagus* spp.) with different adaptive abilities. *Tree Genetics & Genomes*, **8(4)**, 659-673.

Sommer, J.H., H. Kreft, G. Kier, W. Jetz, J. Mutke, and W. Barthlott, 2010: Projected impacts of climate change on regional capacities for global plant species richness. *Proceedings of the Royal Society B*, **277(1692)**, 2271-2280.

Søndergaard, M., J.P. Jensen, and E. Jeppesen, 2003: Role of sediment and internal loading of phosphorus in shallow lakes. *Hydrobiologia*, **506(1-3)**, 135-145.

Sovacool, B.K., 2009: Contextualizing avian mortality: a preliminary appraisal of bird and bat fatalities from wind, fossil-fuel, and nuclear electricity. *Energy Policy*, **32(6)**, 2241-2248.

Sowerby, A., B.A. Emmett, A. Tietema, and C. Beier, 2008: Contrasting effects of repeated summer drought on soil carbon efflux in hydric and mesic heathland soils. *Global Change Biology*, **14(10)**, 2388-2404.

Sowerby, A., B.A. Emmett, D. Williams, C. Beier, and C.D. Evans, 2010: The response of dissolved organic carbon (DOC) and the ecosystem carbon balance to experimental drought in a temperate shrubland. *European Journal of Soil Science*, **61(5)**, 697-709.

Spracklen, D.V., B. Bonn, and K.S. Carslaw, 2008: Boreal forests, aerosols and the impacts on clouds and climate. *Philosophical Transactions of the Royal Society A*, **366(1885)**, 4613-4626.

Stahlschmidt, Z.R., D.F. DeNardo, J.N. Holland, B.P. Kotler, and M. Kruse-Peeples, 2011: Tolerance mechanisms in North American deserts: biological and societal approaches to climate change. *Journal of Arid Environments*, **75(8)**, 681-687.

Staver, A.C., S. Archibald, and S.A. Levin, 2011: The global extent and determinants of savanna and forest as alternative biome states. *Science*, **334(6053)**, 230-232.

Ste-Marie, C., E.A. Nelson, A. Dabros, and M.E. Bonneau, 2011: Assisted migration: introduction to a multifaceted concept. *Forestry Chronicle*, **87(6)**, 724-730.

Steenberg, J.W.N., P.N. Duinker, and P.G. Bush, 2011: Exploring adaptation to climate change in the forests of central Nova Scotia, Canada. *Forest Ecology and Management*, **262(12)**, 2316-2327.

Steffen, W., A. Persson, L. Deutsch, J. Zalasiewicz, M. Williams, K. Richardson, C. Crumley, P. Crutzen, C. Folke, L. Gordon, M. Molina, V. Ramanathan, J. Rockstrom, M. Scheffer, H.J. Schellnhuber, and U. Svedin, 2011: The Anthropocene: from global change to planetary stewardship. *Ambio*, **40(7)**, 739-761.

Steffensen, J.P., K.K. Andersen, M. Bigler, H.B. Clausen, D. Dahl-Jensen, H. Fischer, K. Goto-Azuma, M. Hansson, S.J. Johnsen, J. Jouzel, V. Masson-Delmotte, T. Popp, S.O. Rasmussen, R. Rothlisberger, U. Ruth, B. Stauffer, M.L. Siggaard-Andersen, A.E. Sveinbjornsdottir, A. Svensson, and J.W.C. White, 2008: High-resolution Greenland Ice Core data show abrupt climate change happens in few years. *Science*, **321(5889)**, 680-684.

Stern, N., 2006: *The Economics of Climate Change*. Cambridge University Press, Cambridge, UK, 712 pp.

Stevens, C.J., C. Dupre, E. Dorland, C. Gaudnik, D.J.G. Gowing, A. Bleeker, M. Diekmann, D. Alard, R. Bobbink, D. Fowler, E. Corcket, J.O. Mountford, V. Vandvik, P.A. Aarrestad, S. Muller, and N.B. Dise, 2010: Nitrogen deposition threatens species richness of grasslands across Europe. *Environmental Pollution*, **158(9)**, 2940-2945.

Stevens, V.M., C. Turlure, and M. Baguette, 2010: A meta-analysis of dispersal in butterflies. *Biological Reviews*, **85(3)**, 625-642.

Stewart, I.T., 2009: Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrological Processes*, **23(1)**, 78-94.

Stewart, I.T., D.R. Cayan, and M.D. Dettinger, 2005: Changes toward earlier streamflow timing across western North America. *Journal of Climate*, **18(8)**, 1136-1155.

Stewart, J.B., 1988: Modelling surface conductance of pine forest. *Agricultural and Forest Meteorology*, **43**, 19-35.

Stinson, G., W.A. Kurz, C.E. Smyth, E.T. Neilson, C.C. Dymond, J.M. Metsaranta, C. Goisvenue, C.J. Rampley, Q. Li, T.M. White, and D. Blain, 2011: An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. *Global Change Biology*, **17(6)**, 2227-2244.

Stirling, I. and A.E. Derocher, 2012: Effects of climate warming on polar bears: a review of the evidence. *Global Change Biology*, **18(9)**, 2694-2706.

Stow, D., A. Petersen, A. Hope, R. Engstrom, and L. Coulter, 2007: Greenness trends of Arctic tundra vegetation in the 1990s: comparison of two NDVI data sets from NOAA AVHRR systems. *International Journal of Remote Sensing*, **28**, 4807-4822.

Straile, D., R. Adrian, and D.E. Schindler, 2012: Uniform temperature dependency in the phenology of a keystone herbivore in lakes of the Northern Hemisphere. *PLoS One*, **7(10)**, e45497, doi:10.1371/journal.pone.0045497.

Strayer, D.L. and D. Dudgeon, 2010: Freshwater biodiversity conservation: recent progress and future challenges. *Journal of the North American Benthological Society*, **29(1)**, 344-358.

Sturm, M., J. Schimel, G. Michaelson, J.M. Welker, S.F. Oberbauer, G.E. Liston, J. Fahnestock, and V.E. Romanovsky, 2005: Winter biological processes could help convert arctic tundra to shrubland. *BioScience*, **55(1)**, 17-26.

Suarez, F., D. Binkley, M.W. Kaye, and R. Stottlemyer, 1999: Expansion of forest stands into tundra in the Noatak National Preserve, northwest Alaska. *Ecoscience*, **6(3)**, 465-470.

Suggitt, A.J., C. Stefanescu, F. Paramo, T. Oliver, B.J. Anderson, J.K. Hill, D.B. Roy, T. Brereton, and C.D. Thomas, 2012: Habitat associations of species show consistent but weak responses to climate. *Biology Letters*, **8(4)**, 590-593.

Sunday, J.M., A.E. Bates, and N.K. Dulvy, 2012: Thermal tolerance and the global redistribution of animals. *Nature Climate Change*, **2(9)**, 686-690.

Suttle, K.B., M.A. Thomsen, and M.E. Power, 2007: Species interactions reverse grassland responses to changing climate. *Science*, **315(5812)**, 640-642.

Swab, R.M., H.M. Regan, D.A. Keith, T.J. Regan, and M.K.J. Ooi, 2012: Niche models tell half the story: spatial context and life-history traits influence species responses to global change. *Journal of Biogeography*, **39(7)**, 1266-1277.

Syvitski, J.P.M., A.J. Kettner, I. Overeem, E.W.H. Hutton, M.T. Hannon, G.R. Brakenridge, J. Day, C. Vorosmarty, Y. Saito, L. Giosan, and R.J. Nicholls, 2009: Sinking deltas due to human activities. *Nature Geoscience*, **2(10)**, 681-686.

Szabo, J.K., N. Khwaja, S.T. Garnett, and S.H.M. Butchart, 2012: Global patterns and drivers of avian extinctions at the species and subspecies level. *PLoS One*, **7(10)**, e47080, doi:10.1371/journal.pone.0047080.

Szeicz, J.M. and G.M. Macdonald, 1995: Recent white spruce dynamics at the subarctic alpine treeline of north-western Canada. *Journal of Ecology*, **83(5)**, 873-885.

Tarnocai, C., J.G. Canadell, E.A.G. Schuur, P. Kuhry, G. Mazhitova, and S. Zimov, 2009: Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles*, **23(2)**, GB2023, doi:10.1029/2008GB003327.

Taylor, S., L. Kumar, N. Reid, and D.J. Kriticos, 2012: Climate change and the potential distribution of an invasive shrub, *Lantana camara* L. *PLoS One*, **7(4)**, e35565. doi:10.1371/journal.pone.0035565.

Tchebakova, N.M., E. Parfenova, and A.J. Soja, 2009: The effects of climate, permafrost and fire on vegetation change in Siberia in a changing climate. *Environmental Research Letters*, **4(4)**, 045013, doi:10.1088/1748-9326/4/4/045013.

TEEB, 2009: *TEEB Climate Issues Update. The Economics of Ecosystems and Biodiversity (TEEB).* Hosted by the United Nations Environment Programme (UNEP), UNEP TEEB, Geneva, Switzerland, 32 pp.

Teixiera, E., G. Fischer, H. van Veldhuizen, R. van Dingenen, F. Dentener, G. Mills, C. Walter, and F. Ewert, 2011: Limited potential of crop management for mitigating surface impacts on global food supply. *Atmospheric Environment*, **45(15)**, 2569-2576.

Telwala, Y., B.W. Brook, K. Manish, and M.K. Pandit, 2013: Climate-induced elevational range shifts and increase in plant species richness in a Himalayan biodiversity epicentre. *PLoS One*, **8(2)**, e57103, doi:10.1371/journal.pone.0057103.

ten Brink, P., A. Chiabai, M. Rayment, N. Braeuer, N. Peralta Bezerra, M. Kettunen, and L. Braat, 2008: The cost of policy inaction – in monetary terms. In: *The Cost of Policy Inaction. The Case of Not Meeting the 2010 Biodiversity Target* [Braat, L.L. and P. ten Brink (eds.)]. Alterra-rapport 1718, Alterra, Wageningen University and Research and Institute for European Environmental Policy, Cereales Publishers, Wageningen, Netherlands, pp. 169-224.

Terrier, A., M.P. Girardin, C. Perié, P. Legendre, and Y. Bergeron, 2013: Potential changes in forest composition could reduce impacts of climate change on boreal wildfires. *Ecological Applications*, **23(1)**, 21-35.

Teuling, A.J., M. Hirschi, A. Ohmura, M. Wild, M. Reichstein, P. Ciais, N. Buchmann, C. Ammann, L. Montagnani, A.D. Richardson, G. Wohlfahrt, and S.I. Seneviratne, 2009: A regional perspective on trends in continental evaporation. *Geophysical Research Letters*, **36(2)**, L02404, doi:10.1029/2008GL036584.

Thackeray, S.J., T.H. Sparks, M. Frederiksen, S. Burthe, P.J. Bacon, J.R. Bell, M.S. Botham, T.M. Brereton, P.W. Bright, L. Carvalho, T. Clutton-Brock, A. Dawson, M. Edwards, I.D. Jones, J.T. Jones, D.I. Leech, D.B. Roy, W.A. Scott, M. Smith, R.J. Smithers, I.J. Winfield, and S. Wanless, 2010: Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. *Global Change Biology*, **16(12)**, 3304-3313.

Thaxter, C.B., A.C. Joys, R.D. Gregory, S.R. Baillie, and D.G. Noble, 2010: Hypotheses to explain patterns of population change among breeding bird species in England. *Biological Conservation*, **143(9)**, 2006-2019.

The Royal Society, 2008: *Ground-level Ozone in the 21st Century: Future Trends, Impacts and Policy Implications.* Science Policy Series Report 15/08, London, UK, 132 pp.

Thomas, C.D., A.M.A. Franco, and J.K. Hill, 2006: Range retractions and extinction in the face of climate warming. *Trends in Ecology & Evolution*, **21(8)**, 415-416.

Thomas, C.D., P.K. Gillingham, R.B. Bradbury, D.B. Roy, B.J. Anderson, J.M. Baxter, N.A.D. Bourn, H.Q.P. Crick, R.A. Findon, R. Fox, J.A. Hodgson, A.R. Holt, M.D. Morecroft, N.J. O'Hanlon, T.H. Oliver, J.W. Pearce-Higgins, D.A. Procter, J.A. Thomas, K.J. Walker, C.A. Walmsley, R.J. Wilson, and J.K. Hill, 2012: Protected areas facilitate species' range expansions. *Proceedings of the National Academy of Sciences of the United States of America*, **109(35)**, 14063-14068.

Thomas, J.A., D.J. Simcox, and R.T. Clarke, 2009: Successful conservation of a threatened *Maculinea* butterfly. *Science*, **325(5936)**, 80-83.

Thompson, P.L., M.C. Jacques, and R.D. Vinebrooke, 2008: Impacts of climate warming and nitrogen deposition on alpine plankton in lake and pond habitats: an in vitro experiment. *Arctic Antarctic and Alpine Research*, **40(1)**, 192-198.

Thonicke, K., S. Venevsky, S. Sitch, and W. Cramer, 2001: The role of fire disturbance for global vegetation dynamics: coupling fire into a Dynamic Global Vegetation Model. *Global Ecology and Biogeography*, **10**, 661-667.

Thornton, P.K., J. van de Steeg, A. Notenbaert, and M. Herrero, 2009: The impacts of climate change on livestock and livestock systems in developing countries: a review of what we know and what we need to know. *Agricultural Systems*, **101(3)**, 113-127.

Thorup, K., A.P. Tøttrup, and C. Rahbek, 2007: Patterns of phenological changes in migratory birds. *Oecologia*, **151(4)**, 697-703.

Throop, H.L. and S.R. Archer, 2008: Shrub (*Prosopis velutina*) encroachment in a semidesert grassland: spatial–temporal changes in soil organic carbon and nitrogen pools. *Global Change Biology*, **14(10)**, 2420-2431.

Thuiller, W., S. Lavorel, M.B. Araujo, M.T. Sykes, and I.C. Prentice, 2005: Climate change threats to plant diversity in Europe. *Proceedings of the National Academy of Sciences of the United States of America*, **102(23)**, 8245-8250.

Tian, H.D., L.C. Stige, B. Cazelles, K.L. Kausrud, R. Svarverud, N.C. Stenseth, and Z.B. Zhang, 2011: Reconstruction of a 1,910-y-long locust series reveals consistent associations with climate fluctuations in China. *Proceedings of the National Academy of Sciences of the United States of America*, **108(35)**, 14521-14526.

Tilman, D., C. Balzer, J. Hill, and B.L. Befort, 2011: Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, **108(50)**, 20260-20264.

Tingley, M.W., M.S. Koo, C. Moritz, A.C. Rush, and S.R. Beissinger, 2012: The push and pull of climate change causes heterogeneous shifts in avian elevational ranges. *Global Change Biology*, **18(11)**, 3279-3290.

Tirado, M.C., M.J. Cohen, N. Aberman, J. Meerman, and B. Thompson, 2010: Addressing the challenges of climate change and biofuel production for food and nutrition security. *Food Research International*, **43(7)**, 1729-1744.

Tisseuil, C., M. Vrac, G. Grenouillet, A.J. Wade, M. Gevrey, T. Oberdorff, J.B. Grodwohl, and S. Lek, 2012: Strengthening the link between climate, hydrological and species distribution modeling to assess the impacts of climate change on freshwater biodiversity. *Science of the Total Environment*, **424**, 193-201.

Tng, D.Y.P., B.P. Murphy, E. Weber, G. Sanders, G.J. Williamson, J. Kemp, and D.M.J.S. Bowman, 2012: Humid tropical rain forest has expanded into eucalypt forest and savanna over the last 50 years. *Ecology and Evolution*, **2(1)**, 34-45.

Tockner, K., S.E. Bunn, C. Gordon, R.J. Naiman, G.P. Quinn, and J.A. Stanford, 2008: Floodplains: critically threatened ecosystems. In: *Aquatic Ecosystems. Trends and Global Prospects.* [Polunin, N.V.C. (ed.)]. Cambridge Press, Cambridge, UK, pp. 45-61.

Tomppo, E., T. Gschwantner, M. Lawrence, and R.E. McRoberts (eds.), 2010: *National Forest Inventories – Pathways for Common Reporting*. Springer, New York, NY, USA, 612 pp.

Traill, L.W., C.J.A. Bradshaw, S. Delean, and B.W. Brook, 2010: Wetland conservation and sustainable use under global change: a tropical Australian case study using magpie geese. *Ecography*, **33(5)**, 818-825.

Trathan, P.N., P.T. Fretwell, and B. Stonehouse, 2011: First recorded loss of an emperor penguin colony in the recent period of Antarctic regional warming: implications for other colonies. *PLoS One*, **6(2)**, e14738, doi:10.1371/journal.pone.0014738.

Trivedi, M.R., P.M. Berry, M.D. Morecroft, and T.P. Dawson, 2008: Spatial scale affects bioclimate model projections of climate change impacts on mountain plants. *Global Change Biology*, **14(5)**, 1089-1103.

Tseng, W.C. and C.C. Chen, 2008: Valuing the potential economic impact of climate change on the Taiwan trout. *Ecological Economics*, **65(2)**, 282-291.

Tsoutsos, T., N. Frantzeskaki, and V. Gekas, 2005: Environmental impacts from the solar energy technologies. *Energy Policy*, **33(3)**, 289-296.

Tubby, K.V. and J.F. Webber, 2010: Pests and diseases threatening urban trees under a changing climate. *Forestry*, **83(4)**, 451-459.

Turetsky, M.R., E.S. Kane, J.W. Harden, R.D. Ottmar, K.L. Manies, E. Hoy, and E.S. Kasischke, 2011: Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands. *Nature Geoscience*, **4(1)**, 27-31.

Turner, W.R., B.A. Bradley, L.D. Estes, D.G. Hole, M. Oppenheimer, and D.S. Wilcove, 2010: Climate change: helping nature survive the human response. *Conservation Letters*, **3(5)**, 304-312.

Tylianakis, J.M., R.K. Didham, J. Bascompte, and D.A. Wardle, 2008: Global change and species interactions in terrestrial ecosystems. *Ecology Letters*, **11(12)**, 1351-1363.

Uhl, C. and J.B. Kauffman, 1990: Deforestation, fire susceptibility and potential tree responses to fire in the eastern Amazon. *Ecology*, **71(2)**, 437-449.

UN-HABITAT, 2011: *Cities and Climate Change. Global Report on Human Settlements 2011*. Earthscan, London, UK and Washington DC, USA, 279 pp.

UN DESA Population Division, 2012: *World Urbanization Prospects, the 2011 Revision.* United Nations, Department of Economic and Social Affairs (UN DESA), Population Division, UN Publication, New York, NY, USA, 318 pp.

Urabe, J., J. Togari, and J.J. Elser, 2003: Stoichiometric impacts of increased carbon dioxide on a planktonic herbivore. *Global Change Biology*, **9(6)**, 818-825.

Urban, M.C., M.A. Leibold, P. Amarasekare, L. De Meester, R. Gomulkiewicz, M.E. Hochberg, C.A. Klausmeier, N. Loeuille, C. de Mazancourt, J. Norberg, J.H. Pantel, S.Y. Strauss, M. Vellend, and M.J. Wade, 2008: The evolutionary ecology of metacommunities. *Trends in Ecology & Evolution*, **23(6)**, 311-317.

Urban, M.C., J.J. Tewksbury, and K.S. Sheldon, 2012: On a collision course: competition and dispersal differences create no-analogue communities and cause extinctions during climate change. *Proceedings of the Royal Society B*, **279(1735)**, 2072-2080.

Uys, R.G., J.W. Bond, and T.M. Everson, 2004: The effect of different fire regimes on plant diversity southern African grasslands. *Biological Conservation*, **118(4)**, 489-499.

Vadadi-Fulop, C., C. Sipkay, G. Meszaros, and L. Hufnagel, 2012: Climate change and freshwater zooplankton: what does it boil down to? *Aquatic Ecology*, **46(4)**, 501-519.

Valdes, P., 2011: Built for stability. *Nature Geoscience*, **4(7)**, 414-416.

van Asch, M. and M.E. Visser, 2007: Phenology of forest caterpillars and their host trees: the importance of synchrony. *Annual Review of Entomology*, **52**, 37-55.

van Asch, M., P.H. Tienderen, L.J.M. Holleman, and M.E. Visser, 2007: Predicting adaptation of phenology in response to climate change, an insect herbivore example. *Global Change Biology*, **13(8)**, 1596-1604.

van Asch, M., L. Salis, L.J.M. Holleman, B. van Lith, and M.E. Visser, 2012: Evolutionary response of the egg hatching date of a herbivorous insect under climate change. *Nature Climate Change*, **3**, 244-248.

Van Auken, O.W., 2009: Causes and consequences of woody plant encroachment into western North American grasslands. *Journal of Environmental Management*, **90(10)**, 2931-2942.

van de Waal, D.B., A.M. Verschoor, J.M.H. Verspagen, E. van Donk, and J. Huisman, 2010: Climate-driven changes in the ecological stoichiometry of aquatic ecosystems. *Frontiers in Ecology and the Environment*, **8(3)**, 145-152.

van der Linde, J.A., D.L. Six, M.J. Wingfield, and J. Roux, 2011: *Lasiodiplodia* species associated with dying *Euphorbia ingens* in South Africa. *Southern Forests: a Journal of Forest Science*, **73(3-4)**, 165-173.

van der Molen, M.K., B.J.J.M. van den Hurk, and W. Hazeleger, 2011: A dampened land use change climate response towards the tropics. *Climate Dynamics*, **37(9-10)**, 2035-2043.

van der Werf, G.R., J.T. Randerson, L. Giglio, G.J. Collatz, M. Mu, P.S. Kasibhatla, D.C. Morton, R.S. DeFries, Y. Jin, and T.T. van Leeuwen, 2010: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997-2009). *Atmospheric Chemistry and Physics*, **223**, 11707-11735.

Van Herk, I.G., S.T. Gower, D.R. Bronson, and M.S. Tanner, 2011: Effects of climate warming on canopy water dynamics of a boreal black spruce plantation. *Canadian Journal of Forest Research / Revue Canadienne De Recherche Forestiere*, **41(2)**, 217-227.

van Kleunen, M., E. Weber, and M. Fischer, 2010: A meta-analysis of trait differences between invasive and non-invasive plant species. *Ecology Letters*, **13(2)**, 235-245.

van Mantgem, P.J., N.L. Stephenson, J.C. Byrne, L.D. Daniels, J.F. Franklin, P.Z. Fule, M.E. Harmon, A.J. Larson, J.M. Smith, A.H. Taylor, and T.T. Veblen, 2009: Widespread increase of tree mortality rates in the western United States. *Science*, **323(5913)**, 521-524.

Van Minnen, J.G., B.J. Strengers, B. Eickhout, R.J. Swart, and R. Leemans, 2008: Quantifying the effectiveness of climate change mitigation through forest plantations and carbon sequestration with an integrated land-use model. *Carbon Balance and Management*, **3(1),** 3, doi:10.1186/1750-0680-3-3.

van Vliet, M.T.H., F. Ludwig, J.J.G. Zwolsman, G.P. Weedon, and P. Kabat, 2011: Global river temperatures and sensitivity to atmospheric warming and changes in river flow. *Water Resources Research*, **47(2)**, W02544, doi:10.1029/2010WR009198.

van Vuuren, D.P., M.G.J. den Elzen, P.L. Lucas, B. Eickhout, B.J. Strengers, B. van Ruijven, S. Wonink, and R. van Houdt, 2007: Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Climatic Change*, **81**, 119-159.

van Vuuren, D.P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, T. Masui, N. Nakicenovic, S.J. Smith, and S.K. Rose, 2011: The representative concentration pathways: an overview. *Climatic Change*, **109**, 5-31.

van Wilgen, B.W. and D.M. Richardson, 2012: Three centuries of managing introduced conifers in South Africa: benefits, impacts, changing perceptions and conflict resolution. *Journal of Environmental Management*, **106**, 56-68.

Vaughan, N.E. and T.M. Lenton, 2011: A review of climate geoengineering proposals. *Climatic Change*, **109(3-4)**, 745-790.

Vedder, O., S. Bouwhuis, and B.C. Sheldon, 2013: Quantitative assessment of the importance of phenotypic plasticity in adaptation to climate change in wild bird populations. *PLoS Biol*, **11(7)**, e1001605, doi:10.1371/journal.pbio.1001605.

Veldman, J.W. and F.E. Putz, 2011: Grass-dominated vegetation, not species-diverse natural savanna, replaces degraded tropical forests on the southern edge of the Amazon Basin. *Biological Conservation*, **144(5)**, 1419-1429.

Vennetier, M. and C. Ripert, 2010: Climate change impact on vegetation: lessons from an exceptionally hot and dry decade in south-eastern France. In: *Climate Change and Variability* [Simard, S. (ed.)]. InTech Open, Rijeka, Croatia, pp. 225-242.

Verburg, P., R.E. Hecky, and H. Kling, 2003: Ecological consequences of a century of warming in Lake Tanganyika. *Science*, **301(5632)**, 505-507.

Vieira, G., J. Bockheim, M. Guglielmin, M. Balks, A.A. Abramov, J. Boelhouwers, N. Cannone, L. Ganzert, D.A. Gilichinsky, S. Gotyachkin, J. Lopez-Martinez, I. Meiklejohn, R. Raffi, M. Ramos, C. Schaefer, E. Serrano, F. Simas, R. Sletten, and D. Wagner, 2010: Thermal state of permafrost and active-layer monitoring in the Antarctic: advances during the International Polar Year 2007-2009. *Permafrost and Periglacial Processes*, **21(2)**, 182-197.

Viglizzo, E.F., F.C. Frank, L.V. Carreno, E.G. Jobbagy, H. Pereyra, J. Clatt, D. Pincen, and M.F. Ricard, 2011: Ecological and environmental footprint of 50 years of agricultural expansion in Argentina. *Global Change Biology*, **17(2)**, 959-973.

Vilà-Cabrera, A., J. Martínez-Vilalta, L. Galiano, and J. Retana, 2013: Patterns of forest decline and regeneration across Scots pine populations. *Ecosystems*, **16**, 323-335.

Vinukollu, R.K., R. Meynadier, J. Sheffield, and E.F. Wood, 2011: Multi-model, multi-sensor estimates of global evapotranspiration: climatology, uncertainties and trends. *Hydrological Processes*, **5**, 3993-4010.

Visser, M.E. and C. Both, 2005: Shifts in phenology due to global climate change: the need for a yardstick. *Proceedings of the Royal Society of London Series B*, **272(1665)**, 2561-2569.

Visser, M.E., L.J.M. Holleman, and S.P. Caro, 2009: Temperature has a causal effect on avian timing of reproduction. *Proceedings of the Royal Society B*, **276(1665)**, 2323-2331.

Vitt, P., K. Havens, and O. Hoegh-Guldberg, 2009: Assisted migration: part of an integrated conservation strategy. *Trends in Ecology & Evolution*, **24(9)**, 473-474.

Vitt, P., K. Havens, A.T. Kramer, D. Sollenberger, and E. Yates, 2010: Assisted migration of plants: changes in latitudes, changes in attitudes. *Biological Conservation*, **143(1)**, 18-27.

Volney, W.J.A. and R.A. Fleming, 2007: Spruce budworm (*Choristoneura* spp.) biotype reactions to forest and climate characteristics. *Global Change Biology*, **13(8)**, 1630-1643.

Vongraven, D. and E. Richardson, 2011: Biodiversity – status and trends of polar bears. In: *Arctic Report Card: Update for 2011* [Richter-Menge, J., M.O. Jeffries, and J.E. Overland (eds.)]. National Oceanic and Atmospheric Administration (NOAA) Arctic Research Program, Washington, DC, USA, pp. 75-78, www.arctic.noaa.gov/report11/ArcticReportCard_full_report.pdf.

Vörösmarty, C.J., P. Green, J. Salisbury, and R.B. Lammers, 2000: Global water resources: vulnerability from climate change and population growth. *Science*, **289(5477)**, 284-288.

Vörösmarty, C.J., P.B. McIntyre, M.O. Gessner, D. Dudgeon, A. Prusevich, P. Green, S. Glidden, S.E. Bunn, C.A. Sullivan, C.R. Liermann, and P.M. Davies, 2010: Global threats to human water security and river biodiversity. *Nature*, **467**, pp. 555-561, doi:10.1038/nature09440.

Vredenburg, V.T., R.A. Knapp, T.S. Tunstall, and C.J. Briggs, 2010: Dynamics of an emerging disease drive large-scale amphibian population extinctions. *Proceedings of the National Academy of Sciences of the United States of America*, **107(21)**, 9689-9694.

Wagner, C. and R. Adrian, 2009: Cyanobacteria dominance: quantifying the effects of climate change. *Limnology and Oceanography*, **54(6)**, 2460-2468.

Walker, B. and J.L. Langridge, 1997: Predicting savanna vegetation structure on the basis of plant available moisture (PAM) and plant available nutrients (PAN): a case study from Australia. *Journal of Biogeography*, **24**, 813-825.

Walker, B. and D. Salt, 2006: *Resilience Thinking: Sustaining Ecosystems and People in a Changing World*. Island Press, Washington, DC, USA, 174 pp.

Walker, B., C.S. Holling, S.R. Carpenter, and A. Kinzig, 2004: Resilience, adaptability and transformability in social-ecological systems. *Ecology and Society*, **9(2)**, 5, www.ecologyandsociety.org/vol9/iss2/art5/.

Walker, D.A., H.E. Epstein, M.K. Raynolds, P. Kuss, M.A. Kopecky, G.V. Frost, F.J.A. Daniels, M.O. Leibman, N.G. Moskalenko, G.V. Matyshak, O.V. Khitun, A.V. Khomutov, B.C. Forbes, U.S. Bhatt, A.N. Kade, C.M. Vonlanthen, and L. Tichy, 2012: Environment, vegetation and greenness (NDVI) along the North America and Eurasia Arctic transects. *Environmental Research Letters*, **7(1)**, 015504, doi:10.1088/1748-9326/7/1/015504.

Walker, M.W.C., R.D. Hollister, G.H.R. Henry, L.E. Ahlquist, J.M. Alatalo, M.S. Bret-Harte, M.P. Calef, T.V. Callaghan, A.B. Carroll, H.E. Epstein, I.S. Jonsdottir, J.A. Klein, B. Magnusson, U. Molau, S.F. Oberbauer, S.P. Rewa, C.H. Robinson, G.R. Shaver, K.N. Suding, C.C. Thompson, A. Tolvanen, O. Totland, P.L. Turner, C.E. Tweedie, P.J. Webber, and P.A. Wookey, 2006: Plant community responses to experimental warming across the tundra biome. *Proceedings of the National Academy of Sciences of the United States of America*, **103(5)**, 1342-1346.

Walter, J., K. Grant, C. Beierkuhnlein, J. Kreyling, M. Weber, and A. Jentsch, 2012: Increased rainfall variability reduces biomass and forage quality of temperate grassland largely independent of mowing frequency. *Agriculture Ecosystems & Environment*, **148**, 1-10.

Walters, R.J., W.U. Blanckenhorn, and D. Berger, 2012: Forecasting extinction risk of ectotherms under climate warming: an evolutionary perspective. *Functional Ecology*, **26(6)**, 1324-1338.

Walther, G.-R., S. Berger, and M.T. Sykes, 2005: An ecological 'footprint' of climate change. *Proceedings of the Royal Society B*, **272(1571)**, 1427-1432.

Walther, G.-R., A. Roques, P.E. Hulme, M.T. Sykes, P. Pysek, I. Kuehn, M. Zobel, S. Bacher, Z. Botta-Dukat, H. Bugmann, B. Czucz, J. Dauber, T. Hickler, V. Jarosik, M. Kenis, S. Klotz, D. Minchin, M. Moora, W. Nentwig, J. Ott, V.E. Panov, B. Reineking, C. Robinet, V. Semenchenko, W. Solarz, W. Thuiller, M. Vila, K. Vohland, and J. Settele, 2009: Alien species in a warmer world: risks and opportunities. *Trends in Ecology & Evolution*, **24(12)**, 686-693.

Wang, B., J. Huang, X. Yang, B. Zhang, and M. Liu, 2010: Estimation of biomass, net primary production and net ecosystem production of China's forests based on the 1999–2003 National Forest Inventory. *Scandinavian Journal of Forest Research*, **25(6)**, 544-553.

Wang, K., E.D. Dickinson, M. Wild, and S. Liang, 2010: Evidence for decadal variation in global terrestrial evapotranspiration between 1982 and 2002: 2. Results. *Journal of Geophysical Research: Atmospheres*, **115(D20)**, D20113, doi:10.1029/2010JD013847.

Wang, S., S. Kang, L. Zhang, and F. Li, 2008: Modelling hydrological response to different land-use and climate change scenarios in the Zamu River basin of northwest China. *Hydrological Processes*, **22(14)**, 2502-2510.

Ward, D., 2005: Do we understand the causes of bush encroachment in African savannas? *African Journal of Range and Forage Science*, **22(2)**, 101-105.

Wardle, P. and M.C. Coleman, 1992: Evidence for rising upper limits of four native New Zealand forest trees. *New Zealand Journal of Botany*, **30(3)**, 303-314.

Warren, R., J. Price, A. Fischlin, S.D. Santos, and G. Midgley, 2011: Increasing impacts of climate change upon ecosystems with increasing global mean temperature rise. *Climatic Change*, **106(2)**, 141-177.

Warren, R., J. VanDerWal, J. Price, J.A. Welbergen, I. Atkinson, J. Ramirez-Villegas, T.J. Osborn, A. Jarvis, L.P. Shoo, S.E. Williams, and J. Lowe, 2013: Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. *Nature Climate Change*, **3(7)**, 678-682.

Watrin, J., A.M. Lezine, and C. Hely, 2009: Plant migration and plant communities at the time of the "green Sahara". *Comptes Rendus Geoscience*, **341(8-9)**, 656-670.

Wearn, O.R., D.C. Reuman, and R.M. Ewers, 2012: Extinction debt and windows of conservation opportunity in the Brazilian Amazon. *Science*, **337(6091)**, 228-232.

Webb, B.W. and F. Nobilis, 2007: Long-term changes in river temperature and the influence of climatic and hydrological factors. *Hydrological Sciences Journal / Journal Des Sciences Hydrologiques*, **52(1)**, 74-85.

Welp, L.R., J.T. Randerson, and H.P. Liu, 2007: The sensitivity of carbon fluxes to spring warming and summer drought depends on plant functional type in boreal forest ecosystems. *Agricultural and Forest Meteorology*, **147(3-4)**, 172-185.

Weng, E.S. and G.S. Zhou, 2006: Modeling distribution changes of vegetation in China under future climate change. *Environmental Modeling & Assessment*, **11(1)**, 45-58.

West, J., S.H. Julius, P. Kareiva, C. Enquist, J.J. Lawler, B. Petersen, A.E. Johnson, and M.R. Shaw, 2009: U.S. natural resources and climate change: concepts and approaches for management adaptation. *Environmental Management*, **44(6)**, 1001-1021.

West, J.S., J.A. Townsend, M. Stevens, and B.D.L. Fitt, 2012: Comparative biology of different plant pathogens to estimate effects of climate change on crop diseases in Europe. *European Journal of Plant Pathology*, **133(1)**, 315-331.

Westerling, A., H. Hidalgo, D. Cayan, and T. Swetnam, 2006: Warming and earlier spring increase western U.S. forest wildfire activity. *Science*, **313(5887)**, 940-943.

Westley, F., P. Olsson, C. Folke, T. Homer-Dixon, H. Vredenburg, D. Loorbach, J. Thompson, M. Nilsson, E. Lambin, J. Sendzimir, B. Banerjee, V. Galaz, and S. van der Leeuw, 2011: Tipping toward sustainability: emerging pathways of transformation. *Ambio*, **40(7)**, 762-780.

Weyhenmeyer, G.A., E. Jeppesen, R. Adrian, L. Arvola, T. Blenckner, T. Jankowski, E. Jennings, P. Noges, T. Noges, and D. Straile, 2007: Nitrate-depleted conditions on the increase in shallow northern European lakes. *Limnology and Oceanography*, **52(4)**, 1346-1353.

Weyhenmeyer, G.A., D.M. Livingstone, M. Meili, O. Jensen, B. Benson, and J.J. Magnuson, 2011: Large geographical differences in the sensitivity of ice-covered lakes and rivers in the Northern Hemisphere to temperature changes. *Global Change Biology*, **17(1)**, 268-275.

White, C.R., J.A. Green, G.R. Martin, P.J. Butler, and D. Gremillet, 2013: Energetic constraints may limit the capacity of visually guided predators to respond to Arctic warming. *Journal of Zoology*, **289(2)**, 119-126.

White, M.A., K.M. de Beurs, K. Didan, D.W. Inouye, A.D. Richardson, O.P. Jensen, J. O'Keefe, G. Zhang, R.R. Nemani, W.J.D. van Leeuwen, J.F. Brown, A. de Wit, M. Schaepman, X.M. Lin, M. Dettinger, A.S. Bailey, J. Kimball, M.D. Schwartz, D.D. Baldocchi, J.T. Lee, and W.K. Lauenroth, 2009: Intercomparison, interpretation, and assessment of spring phenology in North America estimated from remote sensing for 1982-2006. *Global Change Biology*, **15(10)**, 2335-2359.

Wickham, J.D., T.G. Wade, and K.H. Riitters, 2012: Empirical analysis of the influence of forest extent on annual and seasonal surface temperatures for the continental United States. *Global Ecology and Biogeography*, **22(5)**, 620-629.

Wiedner, C., J. Rucker, R. Bruggemann, and B. Nixdorf, 2007: Climate change affects timing and size of populations of an invasive cyanobacterium in temperate regions. *Oecologia*, **152(3)**, 473-484.

Wiegand, K., D. Ward, and D. Saltz, 2005: Multi-scale patterns and bush encroachment in an arid savanna with a shallow soil layer. *Journal of Vegetation Science*, **16(3)**, 311-320.

Wiens, J.A., N.E. Seavy, and D. Jongsomjit, 2011: Protected areas in climate space: what will the future bring? *Biological Conservation*, **144(8)**, 2119-2125.

Wigley, B.J., W.J. Bond, and M.T. Hoffman, 2009: Bush encroachment under three contrasting land-use practices in a mesic South African savanna. *African Journal of Ecology*, **47(Suppl s1)**, 62-70.

Wild, M., J. Grieser, and C. Schär, 2008; Combined surface solar brightening and increasing greenhouse effect support recent intensification of the global land-based hydrological circle. *Geophysical Research Letters*, **35(17)**, L17706, doi:10.1029/2008GL034842.

Wiley, M.J., D.W. Hyndman, B.C. Pijanowski, A.D. Kendall, C. Riseng, E.S. Rutherford, S.T. Cheng, M.L. Carlson, J.A. Tyler, R.J. Stevenson, P.J. Steen, P.L. Richards, P.W. Seelbach, J.M. Koches, and R.R. Rediske, 2010: A multi-modeling approach to evaluating climate and land use change impacts in a Great Lakes River Basin. *Hydrobiologia*, **657(1)**, 243-262.

Wilhelm, S. and R. Adrian, 2008: Impact of summer warming on the thermal characteristics of a polymictic lake and consequences for oxygen, nutrients and phytoplankton. *Freshwater Biology*, **53(2)**, 226-237.

Wilkinson, S. and W.J. Davies, 2010: Drought, ozone, ABA and ethylene: new insights from cell to plant to community. *Plant Cell and Environment*, **33(4)**, 510-525.

Williams, A.L., K.E. Wills, J.K. Janes, J.K.V. Schoor, P.C.D. Newton, and M.J. Hovenden, 2007: Warming and free-air CO_2 enrichment alter demographics in four co-occurring grassland species. *New Phytologist*, **176(2)**, 365-374.

Williams, A.P., C.D. Allen, C.I. Millar, T.W. Swetnam, J. Michaelsen, C.J. Still, and S.W. Leavitt, 2010: Forest responses to increasing aridity and warmth in the southwestern United States. *Proceedings of the National Academy of Sciences of the United States of America*, **107(50)**, 21289-21294.

Williams, A.P., C.D. Allen, A.K. Macalady, D. Griffin, C.A. Woodhouse, D.M. Meko, T.W. Swetnam, S.A. Rauscher, R. Seager, H.D. Grissino-Mayer, J.S. Dean, E.R. Cook, C. Gangodagamage, M. Cai, and N.G. McDowell, 2013: Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change*, **3**, 292-297.

Williams, J.W. and S.T. Jackson, 2007: Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology and the Environment*, **5(9)**, 475-482.

Williams, J.W., S.T. Jackson, and J. E. Kutzbach, 2007: Projected distributions of novel and disappearing climates by 2100 AD. *Proceedings of the National Academy of Sciences of the United States of America*, **104(14)**, 5738-5742.

Williams, J.W., B. Shuman, and P.J. Bartlein, 2009: Rapid responses of the prairie-forest ecotone to early Holocene aridity in mid-continental North America. *Global and Planetary Change*, **66(3-4)**, 195-207.

Williams, J.W., B. Shuman, P.J. Bartlein, N.S. Diffenbaugh, and T. Webb, 2010: Rapid, time-transgressive, and variable responses to early Holocene midcontinental drying in North America. *Geology*, **38(2)**, 135-138.

Williams, J.W., J.L. Blois, and B.N. Shuman, 2011: Extrinsic and intrinsic forcing of abrupt ecological change: case studies from the late Quaternary. *Journal of Ecology*, **99(3)**, 664-677.

Willis, C.G., B.R. Ruhfel, R.B. Primack, A.J. Miller-Rushing, J.B. Losos, and C.C. Davis, 2010: Favorable climate change response explains non-native species' success in Thoreau's Woods. *PLoS One*, **5(1)**, e8878, doi:10.1371/journal.pone.0008878.

Willis, C.K.R., R.M.R. Barclay, J.G. Boyles, R.M. Brigham, V. Brack Jr, D.L. Waldien, and J. Reichard, 2010: Bats are not birds and other problems with Sovacool's (2009) analysis of animal fatalities due to electricity generation. *Energy Policy*, **38**, 2067-2069.

Willis, K.J. and S.A. Bhagwat, 2009: Biodiversity and climate change. *Science*, **326(5954)**, 806-807.

Willis, K.J. and G.M. MacDonald, 2011: Long-term ecological records and their relevance to climate change predictions for a warmer world. *Annual Review of Ecology, Evolution, and Systematics*, **42**, 267-287.

Willis, K.J., K.D. Bennett, S.A. Bhagwat, and H.J.B. Birks, 2010: 4 °C and beyond: what did this mean for biodiversity in the past? *Systematics and Biodiversity*, **8(1)**, 3-9.

Willmer, P., 2012: Ecology: pollinator-plant synchrony tested by climate change. *Current Biology*, **22(4)**, R131-R132.

Wilson, R., R. D'Arrigo, B. Buckley, U. Büntgen, J. Esper, D. Frank, B. Luckman, S. Payette, R. Vose, and D. Youngblut, 2007: A matter of divergence: tracking recent warming at hemispheric scales using tree ring data. *Journal of Geophysical Research: Atmospheres*, **112(D17)**, D17103, doi:10.1029/2006JD008318.

Winder, M. and D.E. Schindler, 2004: Climatic effects on the phenology of lake processes. *Global Change Biology*, **10(11)**, 1844-1856.

Winder, M. and U. Sommer, 2012: Phytoplankton response to a changing climate. *Hydrobiologia*, **698(1)**, 5-16.

Winder, M., J.E. Reuter, and S.G. Schladow, 2009: Lake warming favours small-sized planktonic diatom species. *Proceedings of the Royal Society B*, **276(1656)**, 427-435.

Winder, M., A.D. Jassby, and R. Mac Nally, 2011: Synergies between climate anomalies and hydrological modifications facilitate estuarine biotic invasions. *Ecology Letters*, **14(8)**, 749-757.

Winder, R., E.A. Nelson, and T. Beardmore, 2011: Ecological implications for assisted migration in Canadian forests. *Forestry Chronicle*, **87(6)**, 731-744.

Wing, S.L. and E.D. Currano, 2013: Plant response to a global greenhouse event 56 million years ago. *American Journal of Botany*, **100(7)**, 1234-1254.

Wing, S.L., G.J. Harrington, F.A. Smith, J.I. Bloch, D.M. Boyer, and K.H. Freeman, 2005: Transient floral change and rapid global warming at the Paleocene-Eocene boundary. *Science*, **310(5750)**, 993-996.

Winter, M., O. Schweiger, S. Klotz, W. Nentwig, P. Andriopoulos, M. Arianoutsou, C. Basnou, P. Delipetrou, V. Didziulis, M. Hejda, P.E. Hulme, P.W. Lambdon, J. Pergl, P. Pyšek, D.B. Roy, and I. Kühn, 2009: Plant extinctions and introductions lead to phylogenetic and taxonomic homogenization of the European flora. *Proceedings of the National Academy of Sciences of the United States of America*, **106(51)**, 21721-21725.

Wise, M., K. Calvin, A. Thomson, L. Clarke, B. Bond-Lamberty, R. Sands, S.J. Smith, A. Janetos, and J. Edmonds, 2009: Implications of limiting CO_2 concentrations for land use and energy. *Science*, **324(5931)**, 1183-1186.

Witt, G.B., R.A. Harrington, and M.J. Page, 2009: Is 'vegetation thickening' occurring in Queensland's mulga lands – a 50-year aerial photographic analysis. *Australian Journal of Botany*, **57(7)**, 572-582.

Witte, J.C., A.R. Douglass, A. da Silva, O. Torres, R. Levy, and B.N. Duncan, 2011: NASA A-Train and Terra observations of the 2010 Russian wildfires. *Atmospheric Chemistry and Physics*, **11(17)**, 9287-9301.

Wittig, V.E., E.A. Ainsworth, and S.P. Long, 2007: To what extent do current and projected increases in surface ozone affect photosynthesis and stomatal conductance of trees? A meta-analytic review of the last 3 decades of experiments. *Plant, Cell & Environment*, **30(9)**, 1150-1162.

Wittig, V.E., E.A. Ainsworth, S.L. Naidu, D.F. Karnosky, and S.P. Long, 2009: Quantifying the impact of current and future tropospheric ozone on tree biomass, growth physiology and biochemistry. *Global Change Biology*, **15(2)**, 396-424.

Woillez, M.N., M. Kageyama, G. Krinner, N. de Noblet-Ducoudre, N. Viovy, and M. Mancip, 2011: Impact of CO_2 and climate on the Last Glacial Maximum vegetation: results from the ORCHIDEE/IPSL models. *Climate of the Past*, **7(2)**, 557-577.

Wolken, J.M., T.N. Hollingsworth, T.S. Rupp, F.S. Chapin, S.F. Trainor, T.M. Barrett, P.F. Sullivan, A.D. McGuire, E.S. Euskirchen, P.E. Hennon, E.A. Beever, J.S. Conn, L.K. Crone, D.V. D'Amore, N. Fresco, T.A. Hanley, K. Kielland, J.J. Kruse, T. Patterson, E.A.G. Schuur, D.L. Verbyla, and J. Yarie, 2011: Evidence and implications of recent and projected climate change in Alaska's forest ecosystems. *Ecosphere*, **2(11)**, 124, doi:10.1890/ES11-00288.1.

Wolkovich, E.M., B.I. Cook, J.M. Allen, T.M. Crimmins, J.L. Betancourt, S.E. Travers, S. Pau, J. Regetz, T.J. Davies, N.J.B. Kraft, T.R. Ault, K. Bolmgren, S.J. Mazer, G.J. McCabe, B.J. McGill, C. Parmesan, N. Salamin, M.D. Schwartz, and E.E. Cleland, 2012: Warming experiments underpredict plant phenological responses to climate change. *Nature*, **485**, 494-497.

Wood, T.E., M.A. Cavaleri, and S.C. Reed, 2012: Tropical forest carbon balance in a warmer world: a critical review spanning microbial- to ecosystem-scale processes. *Biological Reviews*, **87(4)**, 912-927.

Woodburne, M.O., G.F. Gunnell, and R.K. Stucky, 2009: Climate directly influences Eocene mammal faunal dynamics in North America. *Proceedings of the National Academy of Sciences of the United States of America*, **106(32)**, 13399-13403.

Wookey, P.A., R. Aerts, R.D. Bardgett, F. Baptist, K.A. Brathen, J.H.C. Cornelissen, L. Gough, I.P. Hartley, D.W. Hopkins, S. Lavorel, and G.R. Shaver, 2009: Ecosystem feedbacks and cascade processes: understanding their role in the responses of arctic and alpine ecosystems to environmental change. *Global Change Biology*, **15(5)**, 1153-1172.

Worrall, J.J., G.E. Rehfeldt, A. Hamann, E.H. Hogg, S.B. Marchetti, M. Michaelian, and L.K. Gray, 2013: Recent declines of *Populus tremuloides* in North America linked to climate. *Forest Ecology and Management*, **299**, 35-51.

Wu, C.Y. and J.M. Chen, 2013: Diverse responses of vegetation production to interannual summer drought in North America. *International Journal of Applied Earth Observation and Geoinformation*, **21**, 1-6.

Wu, X.B. and S.R. Archer, 2005: Scale-dependent influence of topography-based hydrologic features on patterns of woody plant encroachment in savanna landscapes. *Landscape Ecology*, **20(6)**, 733-742.

Wu, Z., H. Zhang, C.M. Krause, and N.S. Cobb, 2010: Climate change and human activities: a case study in Xinjiang, China. *Climatic Change*, **99(3-4)**, 457-472.

Xenopoulos, M.A., D.M. Lodge, J. Alcamo, M. Marker, K. Schulze, and D.P. Van Vuuren, 2005: Scenarios of freshwater fish extinctions from climate change and water withdrawal. *Global Change Biology*, **11(10)**, 1557-1564.

Xu, L., R.B. Myneni, F.S. Chapin III, T.V. Callaghan, J.E. Pinzon, C.J. Tucker, Z. Zhu, J. Bi, P. Ciais, H. Tømmervik, E.S. Euskirchen, B.C. Forbes, S.L. Piao, B.T. Anderson, S. Ganguly, R.R. Nemani, S.J. Goetz, P.S.A. Beck, A.G. Bunn, C. Cao, and J.C. Stroeve, 2013: Temperature and vegetation seasonality diminishment over northern lands. *Nature Climate Change*, **3**, 581-586.

Yasuda, M., H. Daimaru, and S. Okitsu, 2007: Detection of alpine moor vegetation change by comparison of orthonized aerophotographs at different times. *Geographical Review of Japan*, **80**, 842-856.

Yi, S.H., M.K. Woo, and M.A. Arain, 2007: Impacts of peat and vegetation on permafrost degradation under climate warming. *Geophysical Research Letters*, **34(16)**, L16504, doi:10.1029/2007GL030550.

Yoshikawa, S. and K. Sanga-Ngoie, 2011: Deforestation dynamics in Mato Grosso in the southern Brazilian Amazon using GIS and NOAA/AVHRR data. *International Journal of Remote Sensing*, **32(2)**, 523-544.

Yvon-Durocher, G., J.M. Montoya, M. Trimmer, and G. Woodward, 2011: Warming alters the size spectrum and shifts the distribution of biomass in freshwater ecosystems. *Global Change Biology*, **17(4)**, 1681-1694.

Zarnetske, P.L., D.K. Skelly, and M.C. Urban, 2012: Biotic multipliers of climate change. *Science*, **336(6088)**, 1516-1518.

Zavaleta, E.S., M.R. Shaw, N.R. Chiariello, B.D. Thomas, E.E. Cleland, C.B. Field, and H.A. Mooney, 2003: Grassland responses to three years of elevated temperature, CO_2, precipitation, and N deposition. *Ecological Monographs*, **73(4)**, 585-604.

Zelazowski, P., Y. Malhi, C. Huntingford, S. Sitch, and J.B. Fisher, 2011: Changes in the potential distribution of humid tropical forests on a warmer planet. *Philosophical Transactions of the Royal Society A*, **369(1934)**, 137-160.

Zeng, Z., S. Piao, X. Lin, G. Yin, S. Peng, P. Ciais, and R.B. Myneni, 2012: Global evapotranspiration over the past three decades: estimation based on the water balance equation combined with empirical models. *Environmental Research Letters*, **7(1)**, 014026, doi:10.1088/1748-9326/7/1/014026.

Zerebecki, R.A. and C.J.B. Sorte, 2011: Temperature tolerance and stress proteins as mechanisms of invasive species success. *PLoS One*, **6(4)**, e14806, doi:10.1371/journal.pone.0014806.

Zhang, H., Y. Li, and X. Gao, 2009: Potential impacts of land-use on climate variability and extremes. *Advances in Atmospheric Sciences*, **26(5)**, 840-854.

Zhang, Y.Y., M. Fischer, V. Colot, and O. Bossdorf, 2013: Epigenetic variation creates potential for evolution of plant phenotypic plasticity. *New Phytologist*, **197(1)**, 314-322.

Zhao, M. and S.W. Running, 2010: Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science*, **329(5994)**, 940-943.

Zhou, G., C. Peng, Y. Li, S. Liu, Q. Zhang, X. Tang, J. Liu, J. Yan, D. Zhang, and G. Chu, 2013: A climate change-induced threat to the ecological resilience of a subtropical monsoon evergreen broad-leaved forest in Southern China. *Global Change Biology*, **19**, 1197-1210.

Zhou, Y.P., K.M. Xu, Y.C. Sud, and A.K. Betts, 2011: Recent trends of the tropical hydrological cycle inferred from Global Precipitation Climatology Project and International Satellite Cloud Climatology Project data. *Journal of Geophysical Research: Atmospheres*, **116(D9)**, D09101, doi:10.1029/2010JD015197.

Zhu, K., C.W. Woodall, and J.S. Clark, 2012: Failure to migrate: lack of tree range expansion in response to climate change. *Global Change Biology*, **18(3)**, 1042-1052.

Zhu, Z.L., Z.Q. Xiong, and G.X. Xing, 2005: Impacts of population growth and economic development on the nitrogen cycle in Asia. *Science in China Series C: Life Sciences*, **48**, 729-737.

Zimmermann, N.E., N.G. Yoccoz, T.C. Edwards, E.S. Meier, W. Thuiller, A. Guisan, D.R. Schmatz, and P.B. Pearman, 2009: Climatic extremes improve predictions of spatial patterns of tree species. *Proceedings of the National Academy of Sciences of the United States of America*, **106**, 19723-19728.

Zimov, N.S., S.A. Zimov, A.E. Zimova, G.M. Zimova, V.I. Chuprynin, and F.S. Chapin, 2009: Carbon storage in permafrost and soils of the mammoth tundra-steppe biome: role in the global carbon budget. *Geophysical Research Letters*, **36(2)**, L02502, doi:10.1029/2008GL036332.

Zurell, D., V. Grimm, E. Rossmanith, N. Zbinden, N.E. Zimmermann, and B. Schroder, 2012: Uncertainty in predictions of range dynamics: black grouse climbing the Swiss Alps. *Ecography*, **35(7)**, 590-603.

Zyryanova, O.A., V. T. Yaborov, T. I. Tchikhacheva, T. Koike, K. Makoto, Y. Matsuura, F. Satoh, and V. I. Zyryanov, 2007: The structure and biodiversity after fire disturbance in *Larix gmelinii* (Rupr.) Rupr. forests, northeasten Asia. *Eurasian Journal of Forest Research*, **10(1)**, 19-29.

5 Coastal Systems and Low-Lying Areas

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This chapter should be cited as:
Wong, P.P., I.J. Losada, J.-P. Gattuso, J. Hinkel, A. Khattabi, K.L. McInnes, Y. Saito, and A. Sallenger, 2014: Coastal systems and low-lying areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 361-409.

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Executive Summary

Coastal systems are particularly sensitive to three key drivers related to climate change: sea level, ocean temperature, and ocean acidity (*very high confidence*). {5.3.2, 5.3.3.4, 5.3.3.5} Despite the lack of attribution of observed coastal changes, there is a long-term commitment to experience the impacts of sea level rise because of a delay in its response to temperature (*high confidence*). {5.5.8} In contrast, coral bleaching and species ranges can be attributed to ocean temperature change and ocean acidity. {5.4.2.2, 5.4.2.4} For many other coastal changes, the impacts of climate change are difficult to tease apart from human-related drivers (e.g., land use change, coastal development, pollution) (*robust evidence*, *high agreement*).

Coastal systems and low-lying areas will increasingly experience adverse impacts such as submergence, coastal flooding, and coastal erosion due to relative sea level rise (RSLR; *very high confidence*). In the absence of adaptation, beaches, sand dunes, and cliffs currently eroding will continue to do so under increasing sea level (*high confidence*). {5.4.2.1, 5.4.2.2} Large spatial variations in the projected sea level rise together with local factors means RSLR at the local scale can vary considerably from projected global mean sea level rise (GMSLR) (*very high confidence*). {5.3.2} Changes in storms and associated storm surges may further contribute to changes in sea level extremes but the small number of regional storm surge studies, and uncertainty in changes in tropical and mid-latitude cyclones at the regional scale, means that there is *low confidence* in projections of storm surge change {5.3.3.2} Both RSLR and impacts are also influenced by a variety of local processes unrelated to climate (e.g., subsidence, glacial isostatic adjustment, sediment transport, coastal development) (*very high confidence*).

Acidification and warming of coastal waters will continue with significant negative consequences for coastal ecosystems (*high confidence*). The increase in acidity will be higher in areas where eutrophication or coastal upwellings are an issue. It will have negative impacts for many calcifying organisms (*high confidence*). {5.4.2.2} Warming and acidification will lead to coral bleaching, mortality, and decreased constructional ability (*high confidence*), making coral reefs the most vulnerable marine ecosystem with little scope for adaptation. {5.4.2.4, Box CC-OA} Temperate seagrass and kelp ecosystems will decline with the increased frequency of heat waves and sea temperature extremes as well as through the impact of invasive subtropical species (*high confidence*). {5.4.2.3}

The population and assets exposed to coastal risks as well as human pressures on coastal ecosystems will increase significantly in the coming decades due to population growth, economic development, and urbanization (*high confidence*). The exposure of people and assets to coastal risks has been rapidly growing and this trend is expected to continue. {5.3.4.1, 5.4.3.1} Humans have been the primary drivers of changes in coastal aquifers, lagoons, estuaries, deltas, and wetlands (*very high confidence*) and are expected to further exacerbate human pressures on coastal ecosystems resulting from excess nutrient input, changes in runoff, and reduced sediment delivery (*high confidence*). {5.3.4.2, 5.3.4.3, 5.3.4.4}

For the 21st century, the benefits of protecting against increased coastal flooding and land loss due to submergence and erosion at the global scale are larger than the social and economic costs of inaction (*limited evidence, high agreement*). Without adaptation, hundreds of millions of people will be affected by coastal flooding and will be displaced due to land loss by year 2100; the majority of those affected are from East, Southeast, and South Asia (*high confidence*). {5.3.4.1, 5.4.3.1} At the same time, protecting against flooding and erosion is considered economically rational for most developed coastlines in many countries under all socioeconomic and sea level rise scenarios analyzed, including for the 21st century GMSLR of above 1 m (*limited evidence*, *high agreement*). {5.5.5}

The relative costs of adaptation vary strongly between and within regions and countries for the 21st century (*high confidence*). Some low-lying developing countries (e.g., Bangladesh, Vietnam) and small islands are expected to face very high impacts and associated annual damage and adaptation costs of several percentage points of gross domestic product (GDP). {5.5.5} Developing countries and small islands within the tropics dependent on coastal tourism will be impacted directly not only by future sea level rise and associated extremes but also by coral bleaching and ocean acidification and associated reductions in tourist arrivals (*high confidence*). {5.4.3.4}

The analysis and implementation of coastal adaptation toward climate-resilient and sustainable coasts has progressed more significantly in developed countries than in developing countries (*high confidence*). Given ample adaptation options, more proactive responses can be made and based on technological, policy related, financial, and institutional support. Observed successful adaptation includes major projects (e.g., Thames Estuary, Venice Lagoon, Delta Works) and specific practices in both developed countries (e.g., Netherlands, Australia) and developing countries (e.g., Bangladesh). {5.5.4.2} More countries and communities carry out coastal adaptation measures including those based on integrated coastal zone management, local communities, ecosystems, and disaster reduction, and these measures are mainstreamed into relevant strategies and management plans (*high confidence*). {5.5.4, 5.5.5}

5.1. Introduction

This chapter presents an updated picture of the impacts, vulnerability, and adaptation of coastal systems and low-lying areas to climate change, with sea level rise perceived as the most important risk for human systems. Unlike the coastal chapter in the previous assessment (Fourth Assessment Report, AR4), materials pertinent to the oceans are not covered here but in two new ocean chapters (Chapters 6 and 30). As in AR4, polar coasts are in another chapter (Chapter 28); small islands are also considered separately (Chapter 29) so an in-depth discussion is not provided herein.

The topics covered in this chapter follow the outline for sectoral chapters approved by the IPCC. An Executive Summary summarizes the key messages with a line of sight to the supporting sections in the chapter.

This chapter consists of six sections, with this first section dealing with progress in knowledge from AR4 to AR5 (Fifth Assessment Report), scope of chapter, and new developments. Section 5.2 defines the coastal systems and climate and non-climate drivers. The coastal systems include both natural systems and human systems, and this division is generally followed throughout the chapter. The climate and non-climate drivers are assessed in Section 5.3, followed by the impacts, vulnerabilities, and risks in Section 5.4. Section 5.5 deals with adaptation and managing risks. Information gaps, data gaps, and research needs are assessed in Section 5.6. There is one box on a specific example and reference to three cross-chapter boxes.

In AR4, the coastal chapter assessed the impact of climate change and a global sea level rise up to 0.59 m in the 2090s. The coastal systems were considered to be affected mainly by higher sea levels, increasing temperatures, changes in precipitation, larger storm surges, and increased ocean acidity. Human activities had continued to increase their pressure on the coasts with rapid urbanization in coastal areas and growth of megacities with consequences on coastal resources. Regionally, South, Southeast, and East Asia; Africa; and small islands were identified as most vulnerable. The AR4 chapter offered a range of adaptation measures, many under the Integrated Coastal Zone Management (ICZM) framework that could be carried out in both developed and developing countries, but recognized that the latter would face more challenges. Various issues on increasing the adaptive capacity or increasing the resilience of coastal communities were discussed. The unavoidability of sea level rise in the long term, even with stringent mitigation, was noted, with adaptation becoming an urgent issue.

A number of key issues related to the coasts have arisen since AR4. There is now better understanding of the natural systems, their ecosystem functions, their services and benefits to humanity, and how they can be affected by climate change. Their linkages landward to the watersheds and seaward to the seas and oceans need to be considered for a more integrated assessment of climate change impacts. The global mean sea level rise (GMSLR) is projected to be 0.28 to 0.98 m by 2100 (Table 5-2), although with regional variations and local factors the local sea level rise can be higher than that projected for the GMSLR. This has serious implications for coastal cities, deltas, and low-lying states. While higher rates of coastal erosion are generally expected under rising sea levels, the complex inter-relationships between the geomorphological and ecological attributes of the coastal system (Gilman et al., 2006; Haslett, 2009) and the relevant climate and oceanic processes need to be better established at regional and local scales. Such complex inter-relationships can be influenced by different methods and responses of coastal management.

Also of concern is ocean acidification. Together with warming, it causes coral reefs to lose their structural integrity, negatively implicating reef communities and shore protection (Sheppard et al., 2005; Manzello et al., 2008; see Boxes CC-OA, CC-CR). Acidification has potential impacts of reduced calcification in shellfish and impacts on commercial aquaculture (Barton et al., 2012). Since AR4, a significant number of new findings regarding the impacts of climate change on human settlements and key coastal systems such as rocky coasts, beaches, estuaries, deltas, salt marshes, mangroves, coral reefs, and submerged vegetation have become available and are reviewed in this chapter. However, uncertainties regarding projections of potential impacts on coastal systems remain generally high.

This chapter also provides advances in both vulnerability assessments and the identification of potential adaptation actions, costs, benefits, and trade-offs. A large number of new studies estimate the costs of inaction versus potential adaptation. Coastal adaptation has become more widely used, with a wider range of approaches and frameworks such as integrated coastal management, ecosystem-based adaptation, community-based adaptation, and disaster risk reduction and management.

Climate change will interact differently with the variety of human activities and other drivers of change along coastlines of developed and developing countries. For example, on the coastlines of developed countries, changes in weather and climate extremes and sea level rise may impact the demand for housing, recreational facilities, and construction of renewable energy infrastructure on the coast (Hadley, 2009), including critical infrastructures such as transportation, ports, and naval bases. Along the coasts of developing countries, weather and climate extremes affect a wide range of economic activities supporting coastal communities and pose an additional risk to many of the fastest growing low-lying urban areas, such as in Bangladesh and China (McGranahan et al., 2007; Smith, 2011).

5.2. Coastal Systems

Coastal systems and low-lying areas, also referred to as coasts in this assessment, include all areas near mean sea level. Generally, there is no single definition for the coast and the coastal zone/area, where the latter emphasizes the area or extent of the coastal ecosystems. In relation to exposure to potential sea level rise, the low-elevation coastal zone (LECZ) has been used in recent years with reference to specific area and population up to 10 m elevation (Vafeidis et al., 2011).

Coastal systems are conceptualized to consist of both natural and human systems (Figure 5-1). The natural systems include distinct coastal features and ecosystems such as rocky coasts, beaches, barriers and sand dunes, estuaries and lagoons, deltas, river mouths, wetlands, and coral reefs. These elements help define the seaward and landward boundaries of the coast. In spite of providing a wide variety of regulating, provisioning, supporting, and cultural services (MEA, 2005), they have

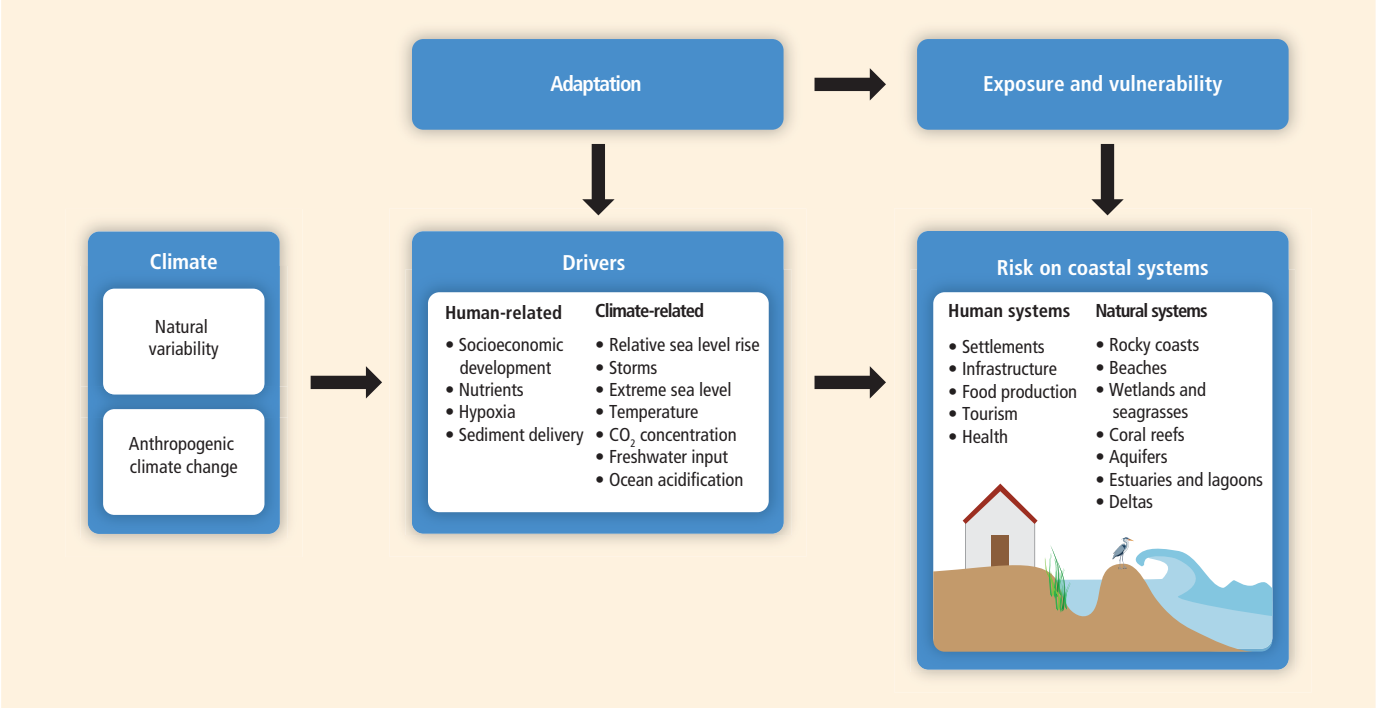

Figure 5-1 | Climate, just as anthropogenic or natural variability, affects both climate and human related drivers. Risk on coastal systems is the outcome of integrating drivers' associated hazards, exposure, and vulnerability. Adaptation options can be implemented either to modify the hazards or exposure and vulnerability, or both.

been altered and heavily influenced by human activities, with climate change constituting only one among many pressures these systems are facing. The human systems include the built environment (e.g., settlements, water, drainage, as well as transportation infrastructure and networks), human activities (e.g., tourism, aquaculture, fisheries), as well as formal and informal institutions that organize human activities (e.g., policies, laws, customs, norms, and culture). The human and natural systems form a tightly coupled socio-ecological system (Berkes and Folke, 1998; Hopkins et al., 2012).

5.3. Drivers

5.3.1. Introduction

In AR4, changes in climate drivers (i.e., any climate-induced factor that directly or indirectly causes a change), including sea level rise, were projected for different Special Report on Emissions Scenarios (SRES) emissions scenarios (IPCC, 2000). Consequently, to date, most of the impacts and vulnerability assessments of climate change in coastal areas are based on SRES A2, A1B, B2, and A1F1 scenarios. Since AR4 a new scenario process has been initiated to replace the SRES scenarios with Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) (Moss et al., 2010). The RCPs are scenarios specifying concentrations, rather than emissions, thereby avoiding differences in concentrations of long-lived greenhouse gas (GHG) and aerosol concentrations for the same emissions scenarios that can arise from the use of different models (van Vuuren et al., 2011). For a comparison between RCP and SRES scenarios, see WGI AR5 Box 1.2. In addition, Extended Concentration Pathways (ECPs) have been introduced for the 2100–2300 period (Meinhausen et al., 2011), providing the opportunity to assess the long-term commitment to sea level rise, which is *virtually certain* to continue beyond 2500 unless global temperature declines (WGI AR5 Chapter 1; Section 13.5.2).

The SSPs provide representative qualitative story lines (narratives) of world development together with quantitative pathways of key socioeconomic variables such as gross domestic product (GDP) and population. A preliminary list of five SSPs has been proposed (Arnell et al., 2011; O'Neill et al., 2012), and work to further refine them is ongoing (Kriegler et al. 2012; Van Vuuren et al., 2012). SSPs do not include assumptions on mitigation policy and are thus independent from RCPs in the sense that the same SSP may lead to different concentration levels and consequently rises in sea level depending on the level of mitigation reached (Arnell et al., 2011; O'Neill et al., 2012). Table 5-1 summarizes the main climate-related drivers for the coastal systems.

5.3.2. Relative Sea Level Rise

Assessments of coastal impacts, vulnerability, and adaptation need to consider relative sea level rise (RSLR), which includes climate-induced GMSLR (Section 5.3.2.1) and regional variations (Section 5.3.2.2) as well as local non-climate-related sea level changes (Section 5.3.2.3). RSLR poses a significant threat to coastal systems and low-lying areas around the globe, leading to inundation and erosion of coastlines and contamination of freshwater reserves and food crops (Nicholls, 2010). Sea level rise due to thermal expansion as the oceans warm, together with meltwater from glaciers, icecaps, and ice sheets of Greenland and Antarctica, are the major factors that contribute to RSLR globally. However, regional variations in the rate of rise occur because of ocean circulation patterns and interannual and decadal variability (e.g., Zhang

Table 5-1 | Main climate-related drivers for coastal systems, their trends due to climate change, and their main physical and ecosystem effects.

Climate-related driver	Physical/chemical effects	Trends	Projections	Progress since AR4
Sea level	Submergence, flood damage, erosion; saltwater intrusion; rising water tables/impeded drainage; wetland loss (and change).	Global mean sea level *very likely* increase (Section 5.3.2.2; WGI AR5 Sections 3.7.2, 3.7.3).	Global mean sea level *very likely* increase (see Table 5.1; WGI AR5 Section 13.5.1). Regional variability (Section 5.3.2.2; WGI AR5 Chapter 13).	Improved confidence in contributions to observed sea level. More information on regional and local sea level rise.
Storms: tropical cyclones (TCs), extratropical cyclones (ETCs)	Storm surges and storm waves, coastal flooding, erosion; saltwater intrusion; rising water tables/impeded drainage; wetland loss (and change). Coastal infrastructure damage and flood defense failure.	TCs (Box 5-1, WGI AR5 Section 2.6.3): *low confidence* in trends in frequency and intensity due to limitations in observations and regional variability. ETCs (Section 5.3.3.1; WGI AR5 Section 2.6.4): *likely* poleward movement of circulation features but *low confidence* in intensity changes.	TCs (Box 5-1): *likely* decrease to no change in frequency; *likely* increase in the most intense TCs. ETCs (Section 5.3.3.1): *high confidence* that reduction of ETCs will be small globally. *Low confidence* in changes in intensity.	Lowering of confidence of observed trends in TCs and ETCs since AR4. More basin-specific information on storm track changes.
Winds	Wind waves, storm surges, coastal currents, land coastal infrastructure damage.	*Low confidence* in trends in mean and extreme wind speeds (Section 5.3.3.2, SREX, WGI AR5 Section 3.4.5).	*Low confidence* in projected mean wind speeds. *Likely* increase in TC extreme wind speeds (Section 5.3.3.2, SREX).	Winds not specifically addressed in AR4.
Waves	Coastal erosion, overtopping and coastal flooding.	*Likely* positive trends in Hs in high latitudes (Section 5.3.3.2; WGI AR5 Section 3.4.5).	*Low confidence* for projections overall but *medium confidence* for Southern Ocean increases in Hs (Section 5.3.3.2).	Large increase in number of wave projection studies since AR4.
Extreme sea levels	Coastal flooding erosion, saltwater intrusion.	*High confidence* of increase due to global mean sea level rise (Section 5.3.3.3; WGI AR5 Chapter 13).	*High confidence* of increase due to global mean sea level rise, *low confidence* of changes due to storm changes (Section 5.3.3.3; WGI AR5 Section 13.5).	Local subsidence is an important contribution to regional sea level rise in many locations.
Sea surface temperature (SST)	Changes to stratification and circulation; reduced incidence of sea ice at higher latitudes; increased coral bleaching and mortality, poleward species migration; increased algal blooms.	*High confidence* that coastal SST increase is higher than global SST increase (Section 5.3.3.4).	*High confidence* that coastal SSTs will increase with projected temperature increase (Section 5.3.3.4).	Emerging information on coastal changes in SSTs.
Freshwater input	Altered flood risk in coastal lowlands; altered water quality/salinity; altered fluvial sediment supply; altered circulation and nutrient supply.	*Medium confidence* (*limited evidence*) in a net declining trend in annual volume of freshwater input (Section 5.3.3.6).	*Medium confidence* for general increase in high latitudes and wet tropics and decrease in other tropical regions (Section 5.3.3.6).	Emerging information on freshwater input.
Ocean acidity	Increased CO_2 fertilization; decreased seawater pH and carbonate ion concentration (or "ocean acidification").	*High confidence* of overall increase, with high local and regional variability (Section 5.3.3.5).	*High confidence* of increase at unprecedented rates but with local and regional variability (Box CC-OA).	Coastal ocean acidification not specifically addressed in AR4. Considerable progress made in chemical projections and biological impacts.

SREX = IPCC 2012 Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation.

and Church, 2012; Ganachaud et al., 2013) and glacial isostatic rebound and tectonic movement. Subsidence of coastal land from sediment compaction due to building loads, harbor dredging, changes in sediment supply that cause erosion/accretion, and subsurface resource extraction (e.g., groundwater, gas and petroleum; Syvitski et al., 2009) may also contribute to RSLR locally and therefore requires consideration in coastal impact studies. Sea level impacts are most pronounced during episodes of extreme sea levels and these are discussed in Section 5.3.3.

5.3.2.1. Global Mean Sea Level

It is *very likely* that global mean sea level rose at a mean rate of 1.7 [1.5 to 1.9] mm yr^{-1} between 1900 and 2010 and at a rate 3.2 [2.8 to 3.6] mm yr^{-1} from 1993 to 2010 (WGI AR5 Section 13.2.2). Ocean thermal expansion and melting of glaciers have been the largest contributors, accounting for more than 80% of the GMSLR over the latter period (WGI AR5 Section 13.3.1). Future rates of GMSLR during the 21st century are projected to exceed the observed rate for the period 1971–2010 of 2.0 [1.7 to 2.3] mm yr^{-1} for all RCP scenarios (WGI AR5 Table 13.1). Table 5-2 summarizes the *likely* ranges of 21st century GMSLR as established by the Working Group I contribution to this Assessment Report.

From a coastal risk management perspective (Nicholls et al., 2013) assessments of impacts, vulnerabilities, and adaptation have been using GMSLR scenarios above the ranges put forward by WGI reports of AR4 (Meehl et al., 2007; Table 10.7) and AR5 (WGI AR5 Table 13.5). The ranges estimated by WGI of AR4 and AR5 include only those components of GMSLR that can be quantified using process-based models (i.e., models derived from the laws of physics; WGI AR5 Glossary). The ranges given in AR4 thus explicitly excluded contributions to GMSLR resulting from changes in ice flows from the ice sheets of Greenland and Antarctica because at that time process-based models were not able to assess this with sufficient confidence (Meehl et al., 2007; WGI AR5 Section 4.4.5). Since then, understanding has increased and the *likely* range of GMSLR given in AR5 now includes ice sheet flow contributions. *Likely*, however,

means that there is still a 0 to 33% probability of GMSLR beyond this range, and coastal risk management needs to consider this. WGI does not assign probabilities to GMSLR beyond the *likely* range, because this cannot be done with the available process-based models. WGI, however, assigns *medium confidence* that 21st century GMSLR does not exceed the likely range by several tenths of a meter (WGI AR5 Section 13.5.1). When using other approaches such as semi-empirical models, evidence from past climates and physical constraints on ice-sheet dynamics GMSLR upper bounds of up to 2.4 m by 2100 have been estimated, but there is *low agreement* on these higher estimates and no consensus on a 21st century upper bound (WGI AR5 Section 13.5.3). Coastal risk management is thus left to choose an upper bound of GMSLR to consider based on which level of risk is judged to be acceptable in the specific case. The Dutch Delta Programme, for example, considered a 21st century GMSLR of 1.3 m as the upper bound.

It is *virtually certain* that sea level rise will continue beyond the 21st century, although projections beyond 2100 are based on fewer and simpler models that include lower resolution coupled climate models for thermal expansion and ice sheet models coupled to climate models to project ice sheet contributions. The basis for the projections are the Extended Concentration Pathways (ECPs), and projections are provided for low, medium, and high scenarios that relate to atmospheric GHG concentrations <500, 500 to 700, and >700 ppm respectively (WGI AR5 Section 13.5.2). Projections of GMSLR up to 2500 are also summarized in Table 5-2.

5.3.2.2. Regional Sea Level

Sea level rise will not be uniform in space and time. Natural modes of climate variability influence sea levels in different regions of the globe and this will affect the rate of rise on interannual and interdecadal time periods. For example, in the equatorial Pacific, sea levels can vary from the global mean by up to 40 cm due to El Niño-Southern Oscillation (ENSO; e.g., Walsh et al., 2012) and this can strongly influence trends on decadal scales. Regional variations in the rate of sea level rise on the coast can arise from climate and ocean dynamic processes such as changes in winds and air pressure, air-sea heat and freshwater fluxes, and ocean currents and their steric properties (Timmermann et al., 2010; WGI AR5 FAQ 13.1). Although the vast majority of coastlines are experiencing sea level rise, coastlines near current and former glaciers and ice sheets are experiencing relative sea level fall (Milne et al., 2009; WGI AR5 FAQ 13.1). This is because the gravitational attraction of the ice sheet decreases as it melts and exerts less pull on the oceans and also because the land tends to rise as the ice melts, the shape of the sea floor changes under the reduced load of the ice sheets, and the change in mass distribution alters the Earth's rotation (WGI AR5 FAQ 13.1; Gomez et al., 2010). In terms of absolute sea level change, approximately 70% of the global coastlines are projected to experience sea level change that is within 20% of the global mean sea level change (WGI AR5 Section 13.6.5).

5.3.2.3. Local Sea Level

Besides the effect of long-term vertical land movement on regional sea level, RSLR can occur locally due to subsidence or uplifts of coastal plains as well as due to other natural causes. Natural subsidence can occur because of sediment compaction and loading, as in the Mississippi River, and other deltas (Törnqvist et al., 2008; Dokka, 2011; Marriner et al., 2012). Tectonic movements, both sustained and abrupt, have brought about relative sea level changes. The Great East Japan Earthquake in 2011 caused subsidence of up to 1.2 m of the Pacific coast of northeast Japan (Geospatial Information Authority of Japan, 2011). The Sumatra-Andaman earthquake in 2004 and subsequent earthquakes in 2005 produced vertical deformation ranging from uplift of 3 m to subsidence of 1 m (Briggs et al., 2006). These movements are especially important in coastal zones located near active plate margins.

Anthropogenic causes of RSLR include sediment consolidation from building loads, reduced sediment delivery to the coast, and extraction of subsurface resources such as gas, petroleum, and groundwater. Subsidence rates may also be sensitive to the rates of oil and gas removal (e.g., Kolker et al., 2011). Syvitski et al. (2009) estimate that the majority of the world's largest deltas are currently subsiding at rates that are considerably larger than the current rates of sea level rise because of coastal sediment starvation due to substantial dam building over the 20th century or sediment compaction through natural or anthropogenic activities. Many large cities on deltas and coastal plains have subsided during the last 100 years: ~4.4 m in eastern Tokyo, ~3 m in the Po delta, ~2.6 m in Shanghai, and ~1.6 m in Bangkok (Syvitski et al., 2009; Teatini et al., 2011). Loads from massive buildings and other large structures can also increase sediment compaction and subsidence (Mazzotti et al., 2009). RSLR can exceed GMSLR by an order of magnitude, reaching more than 10 cm yr^{-1}, and it is estimated that the delta surface

Table 5-2 | Projections of global mean sea level rise in meters relative to 1986–2005 are based on ocean thermal expansion calculated from climate models, the contributions from glaciers, Greenland and Antarctica from surface mass balance calculations using climate model temperature projections, the range of the contribution from Greenland and Antarctica due to dynamical processes, and the terrestrial contribution to sea levels, estimated from available studies. For sea levels up to and including 2100, the central values and the 5–95% range are given whereas for projections from 2200 onwards, the range represents the model spread due to the small number of model projections available and the high scenario includes projections based on RCP6.0 and RCP8.5. Source: WGI AR5 Summary for Policymakers and Sections 12.4.1, 13.5.1, and 13.5.4.

Emission scenario	Representative Concentration Pathway (RCP)	2100 CO_2 concentration (ppm)	Mean sea level rise (m)		Emission scenario	Mean sea level rise (m)		
			2046–2065	2100		2200	2300	2500
Low	2.6	421	0.24 [0.17–0.32]	0.44 [0.28–0.61]	Low	0.35–0.72	0.41–0.85	0.50–1.02
Medium low	4.5	538	0.26 [0.19–0.33]	0.53 [0.36–0.71]	Medium	0.26–1.09	0.27–1.51	0.18–2.32
Medium high	6.0	670	0.25 [0.18–0.32]	0.55 [0.38–0.73]	High	0.58–2.03	0.92–3.59	1.51–6.63
High	8.5	936	0.29 [0.22–0.38]	0.74 [0.52–0.98]				

area vulnerable to flooding could increase by 50% for 33 deltas around the world under the sea level rise as projected for 2100 by the IPCC AR4 (Syvitski et al., 2009).

Clearly large regional variations in the projected sea level rise, together with local factors such as subsidence, indicates that RSLR can be much larger than projected GMSLR and therefore is an important consideration in impact assessments (*very high confidence*).

5.3.3. Climate-Related Drivers

Increasing GHGs in the atmosphere produce changes in the climate system on a range of time scales that impact the coastal physical environment. On shorter time scales, physical coastal impacts such as inundation, erosion, and coastal flooding arise from severe storm-induced surges, wave overtopping, and rainfall runoff. On longer time scales, wind and wave climate change can cause changes in sediment transport at the coast and associated changes in erosion or accretion. Natural modes of climate variability, which can affect severe storm behavior and wind and wave climate, may also undergo anthropogenic changes in the future. Ocean and atmospheric temperature change can affect species distribution with impacts on coastal biodiversity. Carbon dioxide (CO_2) uptake in the ocean increases ocean acidity and reduces the saturation state of carbonate minerals, essential for shell and skeletal formation in many coastal species. Changes in freshwater input can alter coastal ocean salinity concentrations. Past and future changes to these physical drivers are discussed in this section (see also Table 5-1).

5.3.3.1. Severe Storms

Severe storms such as tropical and extratropical cyclones (ETCs) can generate storm surges over coastal seas. The severity of these depends on the storm track, regional bathymetry, nearshore hydrodynamics, and the contribution from waves. Globally there is *low confidence* regarding changes in tropical cyclone activity over the 20th century owing to changes in observational capabilities, although it is *virtually certain* that there has been an increase in the frequency and intensity of the strongest tropical cyclones in the North Atlantic since the 1970s (WGI AR5 Section 2.6). In the future, it is *likely* that the frequency of tropical cyclones globally will either decrease or remain unchanged, but there will be a *likely* increase in global mean tropical cyclone precipitation rates and maximum wind speed (WGI AR5 Section 14.6).

ETCs occur throughout the mid-latitudes of both hemispheres, and their development is linked to large-scale circulation patterns. Assessment of changes in these circulation features reveals a widening of the tropical belt, poleward shift of storm tracks and jet streams, and contraction of the polar vortex; this leads to the assessment that it is *likely* that, in a zonal mean sense, circulation features have moved poleward (WGI AR5 Sections 2.7.5 to 2.7.8) but there is *low confidence* regarding regional changes in intensity of ETCs (e.g., Seneviratne et al., 2012). With regard to future changes, a small poleward shift is *likely* in the Southern Hemisphere but changes in the Northern Hemisphere are basin specific and of *lower confidence* (WGI AR5 Section 14.6.3). Globally, it is *unlikely* that the number of ETCs will fall by more than a few percent due to anthropogenic climate change (*high confidence*; WGI AR5 Section 14.6.3).

5.3.3.2. Extreme Sea Levels

Extreme sea levels are those that arise from combinations of factors including astronomical tides, storm surges, wind waves and swell, and interannual variability in sea levels. Storm surges are caused by the falling atmospheric pressures and surface wind stress associated with storms such as tropical and ETCs and therefore may change if storms are affected by climate change. To date, however, observed trends in extreme sea levels are mainly consistent with mean sea level (MSL) trends (e.g., Marcos et al., 2009; Haigh et al., 2010; Menendez and Woodworth, 2010; Losada et al., 2013) indicating that MSL trends rather than changes in weather patterns are responsible.

Assuming that sea level extremes follow a simple extreme value distribution (i.e., a Gumbel distribution), and accounting for the uncertainty in projections of future sea level rise, Hunter (2012) has developed a technique for estimating a sea level allowance, that is, the minimum height that structures would need to be raised in a future period so that the number of exceedances of that height remains the same as under present climate conditions (Figure 5-2). Such an allowance can be factored into adaptive responses to rising sea levels. It should be noted, however, that extreme sea level distributions might not follow a simple Gumbel distribution (e.g., Tebaldi et al., 2012) owing to different factors influencing extreme levels that may not be measured by tide gauges (e.g., Hoeke et al., 2013).

Regarding future changes to storm surges, hydrodynamic models forced by climate models have been used in several extratropical regional studies such as the northeast Atlantic (e.g., Debenard and Roed, 2008; Wang et al., 2008; Sterl et al., 2009) and southern Australia (Colberg and McInnes, 2012). These studies show strong regional variability and sensitivity to the choice of Global Climate Model (GCM) or Regional Climate Model (RCM). The effect of future tropical cyclone changes on storm surges has also been investigated in a number of regions using a range of different methods. These include methods to stochastically generate and/or perturb cyclones within background environmental conditions that represent historical (e.g., Harper et al., 2009) and GCM-represented future conditions (e.g., Mousavi et al., 2011; Lin et al., 2012). Regional studies include Australia's tropical east coast (Harper et al., 2009), Louisiana (Smith et al., 2010), Gulf of Mexico (Mousavi et al., 2011), India (Unnikrishnan et al., 2011), and New York (Lin et al., 2012), and the details of the methods and findings vary considerably between the studies. While some studies indicate for some regions increase to extreme sea levels due to changes in storms, others indicate the opposite. In general, the small number of regional storm surge studies together with the different atmospheric forcing factors and modeling approaches means that there is *low confidence* in projections of storm surges due to changes in storm characteristics. However, observed upward trends in MSL together with projected increases for 2100 and beyond indicate that coastal systems and low-lying areas will increasingly experience extreme sea levels and their adverse impacts (*high confidence*) (see also WGI AR5 Section 13.7).

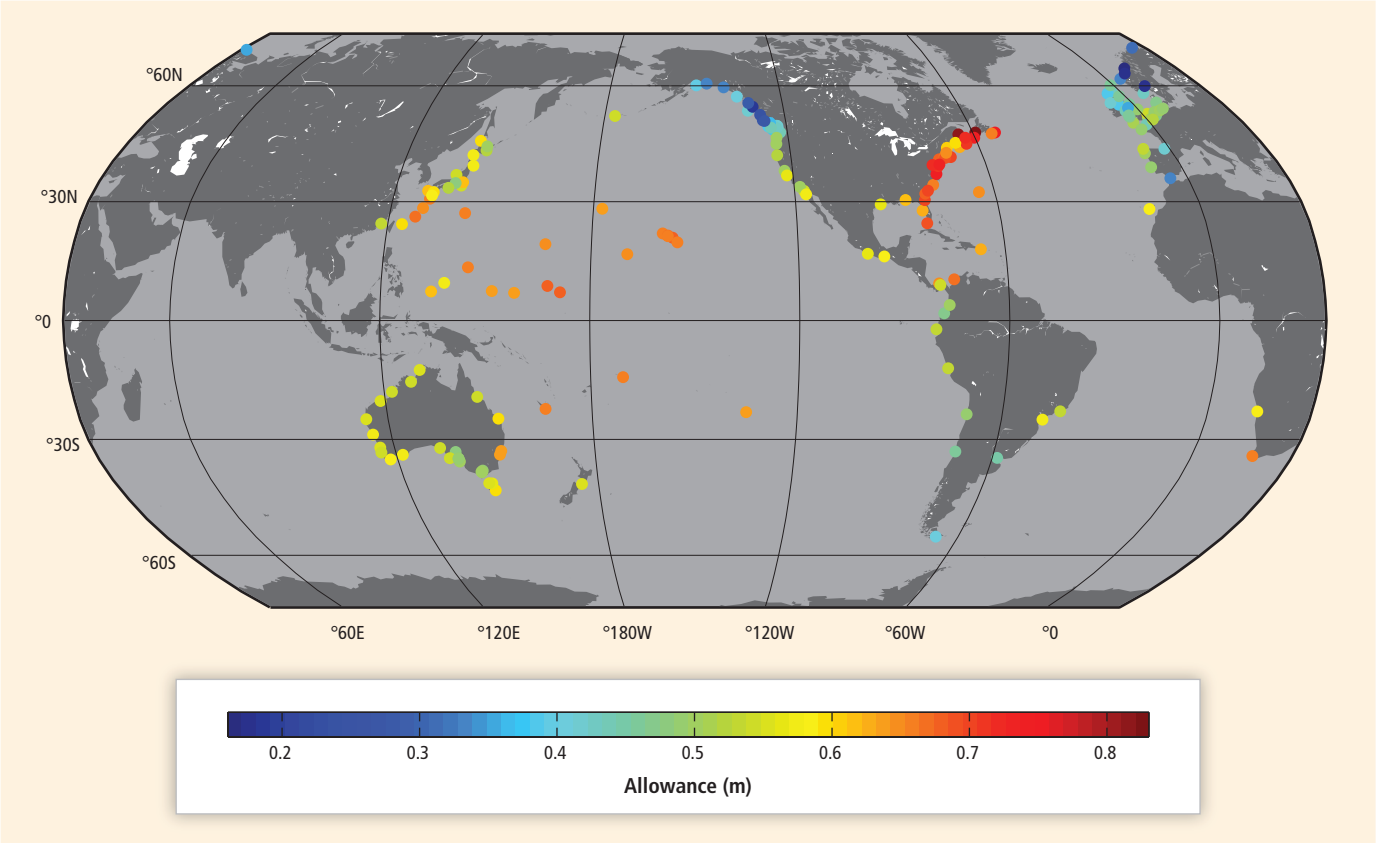

Figure 5-2 | The estimated increase in height (m) that flood protection structures would need to be raised in the 2081–2100 period to preserve the same frequency of exceedances that was experienced for the 1986–2005 period, shown for 182 tide gauge locations and assuming regionally varying relative sea level rise projections under an Representative Concentration Pathway 4.5 (RCP4.5) scenario (adapted from Hunter et al., 2013).

5.3.3.3. Winds and Waves

Changes in wind climate affect large-scale wave climate. Winds also influence longshore current regimes and hence upwelling systems (Narayan et al., 2010; Miranda et al., 2012; see also Sections 6.3.3, 6.3.5). Energy dissipation via wave breaking contributes to longshore and cross-shore currents, elevated coastal sea levels through wave set-up, and run-up and beach erosion. Changes to wind and wave climate therefore can affect sediment dynamics and shoreline processes (e.g., Aargaard et al., 2004; Reguero et al., 2013), and extreme winds and waves are a threat to coastal populations. The coastal impacts of wave climate change are also a function of wave direction and period as well as the coastline itself, which can influence shoaling and refraction. Long period swell, which dominates the wave energy field, poses a significant danger to coastal and offshore structures and shipping (e.g., Semedo et al., 2011) and can causes significant flooding of coastlines with steep shelf margins (Hoeke et al., 2013).

There is *low confidence* in trends calculated from measurements of mean and extreme winds and their causes due to the limited length of records and uncertainties associated with different wind measurement techniques (Seneviratne et al., 2012). However, there is increasing evidence for a strengthening wind stress field in the Southern Ocean since the early 1980s from atmospheric reanalyses, satellite observations, and island station data (WGI AR5 Section 3.4.5). Positive trends in wave height have been detected in the Northeast Atlantic over the 1958–2002 period based on reanalyses and ship observations and in the Southern Ocean between 1985 and 2008 based on satellite data (*medium confidence*) (WGI AR5 Section 3.4.6; see Table 5-2).

Projected changes in mean and extreme winds and waves were assigned *low confidence* (Seneviratne et al., 2012) owing to limited studies. Although there has been an increase in studies addressing future wave climate change (Hemer et al., 2013), generally *low confidence* remains in projected wave climate change (except for *medium confidence* over the Southern Ocean), and this is due to uncertainties in future winds, particularly those associated with storms (see WGI AR5 Section 13.7).

5.3.3.4. Sea Surface Temperature

Sea surface temperature (SST) has significantly warmed during the past 30 years along more than 70% of the world's coastlines, with highly heterogeneous rates of change both spatially and seasonally (Lima and Wethey, 2012). The average rate is 0.18 ± 0.16°C per decade and the average change in seasonal timing was -3.3 ± 4.4 days per decade. These values are larger than in the global ocean where the average of change is 0.11 [0.09 to 0.13]°C per decade in the upper 75 m of the ocean during the 1971–2010 period (WGI AR5 Section 3.2.2) and the seasonal shift is -2.3 days per decade (Lima and Wethey, 2012). Extreme

events have also been reported. For example, the record high ocean temperatures along the western Australian coast during the austral summer of 2010/2011, with nearshore temperatures peaking at about 5°C above average, were unprecedented (Pearce and Feng, 2013). In summary, positive trends in coastal SSTs are seen on the majority of coastlines, and the rate of rise along coastlines is higher on average than the oceans (*high confidence*). Based on projected temperature increases there is *high confidence* that positive coastal SST trends will continue.

5.3.3.5. Ocean Acidification

Anthropogenic ocean acidification refers to the changes in the carbonate chemistry primarily due to the uptake of atmospheric CO_2 (Box CC-OA). Seawater pH exhibits a much larger spatial and temporal variability in coastal waters compared to open ocean owing to the variable contribution of processes other than CO_2 uptake (Duarte et al., 2013a) such as upwelling intensity (Feely et al., 2008; Box CC-UP), deposition of atmospheric nitrogen and sulfur (Doney et al., 2007), carbonate chemistry of riverine waters (Salisbury et al., 2008; Aufdenkampe et al., 2011), as well as inputs of nutrients and organic matter (Borges, 2011; Cai et al., 2011). For example, pH (NBS scale) ranges from 6 to 9 in 24 estuaries (Borges and Abril, 2011) and short-term (hours to weeks) changes of up to 0.5 pH units are not unusual in coastal ecosystems (Hofmann et al., 2011).

Few high-quality ocean acidification time series exceed 5 years in the coastal ocean (Wootton et al., 2008; Provoost et al., 2010; Waldbusser et al., 2010). Some exhibit considerable differences compared to open ocean stations, illustrating that anthropogenic ocean acidification can be lessened or enhanced by processes such as primary production, respiration, and calcification (Borges and Gypens, 2010; Kleypas et al., 2011).

Under the IS92a CO_2 emission scenario, the global pH (total scale) of coastal waters has been projected to decrease from about 8.16 in the year 1850 to 7.83 in 2100 (Lerman et al., 2011) but with considerable spatial variability. For example, using the same CO_2 emission scenario, Cai et al. (2011) projected an overall decline of pH in the Northern Gulf of Mexico of 0.74 over the same period, a value that is much greater than that of the open ocean (Box CC-OA).

To summarize, seawater pH exhibits considerable temporal and spatial variability in coastal areas compared to open ocean owing to additional natural and human influences (*very high confidence*). Coastal acidification is projected to continue but with large and uncertain regional and local variations (*high confidence*).

5.3.3.6. Freshwater Input

Changes in river runoff arise from changes in climate drivers such as precipitation, complex interactions between changing levels of CO_2, plant physiology, and, consequently, evapotranspiration (e.g., Gedney et al., 2006; Betts et al., 2007) as well as human drivers such as land use change, water withdrawal, dam building, and other engineered modifications to waterways (see more detailed discussion in Chapter 3).

An assessment of runoff trends in 925 of the world's largest ocean-reaching rivers, which account for about 73% of global total runoff, indicates that from 1948–2004 statistically significant trends were present in only one-third of the top 200 rivers and, of these, two-thirds exhibited downward trends and one-third upward trends (Dai et al., 2009). While precipitation changes dominate freshwater flows, decreasing trends in river discharges may be further enhanced as a result of human pressures (Dai et al., 2009; Section 3.2.3).

Average annual runoff is generally projected to increase at high latitudes and in the wet tropics and to decrease in most dry tropical regions (Section 3.4.5). Shifts to earlier peak flows are also projected in areas affected by snowmelt (Adam et al, 2009). However, there are some regions where there is considerable uncertainty in the magnitude and direction of change, specifically South Asia and large parts of South America. Both the patterns of change and the uncertainty are largely driven by projected changes in precipitation.

To summarize, there is *medium confidence* (*limited evidence*, *high agreement*) in a net declining trend in freshwater input globally, although large regional variability exists. Trends are dominated by precipitation changes although human pressures on water supply may enhance downward trends (*medium confidence*). Uncertainty in future changes in runoff is linked to precipitation uncertainty. Runoff is generally projected to increase in high latitudes with earlier peak flows and in the wet tropics and decrease in other tropical regions, however, with large uncertainty (*medium confidence*).

5.3.4. Human-Related Drivers

Coastal systems are subject to a wide range of human-related or anthropogenic drivers (e.g., Crain et al., 2009) that interact with climate-related drivers and confound efforts to attribute impacts to climate change. Some of the major terrestrially based human drivers that directly or indirectly cause changes are briefly reviewed. Related drivers in the marine environment are discussed in Sections 6.4 and 30.6.

5.3.4.1. Socioeconomic Development

Socioeconomic development (SED) drives coastal impacts in several ways. SED influences the number of people and the value of assets exposed to coastal hazards. Since AR4, a number of studies have estimated the influence of future sea level rise and associated hazards on coastal population and assets. Although these estimates are subject to uncertainties associated with global elevation and population data sets (Lichter et al., 2011; Mondal and Tatem, 2012), all the studies indicate high and growing exposure of low-lying coastal areas. The Low Elevation Coastal Zone (LECZ) constitutes 2% of the world's land area but contains 10% of the world's population (600 million) and 13% of the world's urban population (360 million), based on year 2000 estimates (McGranahan et al., 2007). About 65% of the world's cities with populations of greater than 5 million are located in the LECZ (McGranahan et al., 2007). The global population exposed to the 1-in-100-year extreme sea level (i.e., the sea level that has a 1% chance of being exceeded every year) has increased by 95% from 1970 to 2010,

with about 270 million people and US$13 trillion worth of assets being exposed to the 1-in-100-year extreme sea level in 2010 (Jongman et al., 2012). In 2002, about US$1.9 trillion worth of assets below the 1-in-100-year extreme sea level were concentrated in the following 10 port cities: Miami (USA), New York-Newark (USA), New Orleans (USA), Osaka-Kobe (Japan), Tokyo (Japan), Amsterdam (Netherlands), Rotterdam (Netherlands), Nagoya (Japan), Virginia Beach (USA), and Guangzhou (China) (Hanson et al., 2011). Compared to other regions, Asia exhibits the greatest exposure in terms of population and assets (Jongman et al., 2012).

For many locations, population and assets exposure is growing faster than the national average trends owing to coastward migration, coastal industrialization, and urbanization (e.g., McGranahan et al., 2007; Seto, 2011; Smith, 2011; see also Chapter 8; *high confidence*). Coastal net migration has largely taken place in flood- and cyclone-prone areas, which poses a challenge for adaptation (de Sherbinin et al., 2011). These processes and associated land use changes are driven by a combination of many social, economic, and institutional factors including taxes, subsidies, insurance schemes, aesthetic and recreational attractiveness of the coast, and increased mobility (Bagstad et al., 2007; Palmer et al., 2011). In China, the country with the largest exposed population, urbanization and land reclamation are the major drivers of coastal land use change (Zhu et al., 2012). Although coastal migration is expected to continue in the coming decades, it is difficult to capture this process in global scenarios, as the drivers of migration and urbanization are complex and variable (Black et al., 2011).

SED also influences the capacity to adapt. Poor people living in urban informal settlements, of which there are about 1 billion worldwide, are particularly vulnerable to weather and climate impacts (de Sherbinin et al., 2011; Handmer et al., 2012). The top five nations classified by population in coastal low-lying areas are developing and newly industrialized countries: Bangladesh, China, Vietnam, India, and Indonesia (McGranahan et al., 2007; Bollman et al., 2010; Jongman et al., 2012). SED and associated land reclamation are also major drivers of the destruction of coastal wetlands, which also makes human settlements more vulnerable because wetlands act as natural buffers reducing wave and storm impacts on the coast (e.g., Crain et al., 2009; Shepard et al., 2011; Arkema et al., 2013; Duarte et al., 2013b). Finally, socioeconomic development is expected to exacerbate further a number of human pressures on coastal systems related to nutrient loads, hypoxia, and sediment delivery, which is discussed in the following subsections.

5.3.4.2. Nutrients

Increased river nutrient (nitrogen, phosphorus) loads to coasts in many regions are observed, and simulated by regional and global models (Alexander et al., 2008; Seitzinger et al., 2010). Anthropogenic global loads of dissolved inorganic nutrients (DIN, DIP) are two to three times larger than those of natural sources (Seitzinger et al., 2010), causing coastal ecosystem degradation (Sections 5.3.4.3, 5.4.2.6). Large variations exist in magnitude and relative sources of nutrient loads. Anthropogenic sources are related primarily to fertilizer use in agriculture and fossil fuel emissions (NO_x) (Galloway et al., 2004; Bouwman et al., 2009). Future trends depend on measures available to optimize nutrient use in crop production and minimize loss to rivers from agriculture (crop, livestock), sewage, and NO_x emissions. In scenarios with little emphasis on nutrient management, global nutrient discharge increases (DIN 29%, DIP 64%) between 2000 and 2050 (Seitzinger et al., 2010). With ambitious nutrient management, global DIN loads decrease slightly and DIP increases (35%). Climate change is projected to change water runoff (Chapter 3) that influences river nutrient loads. Studies of climate change effects related to increased watershed nutrient sources are needed. In summary, nutrient loads have increased in many world regions (*high confidence*); future increases will depend largely on nutrient management practices (*medium confidence*).

5.3.4.3. Hypoxia

The presence of excessive nutrients in coastal waters, which causes eutrophication and the subsequent decomposition of organic matter, is the primary cause of decreased oxygen concentration (hypoxia). Globally, upwelling of low oxygen waters (e.g., Grantham et al., 2004) and ocean warming, which decreases the solubility of oxygen in seawater (Shaffer et al., 2009), are secondary drivers but can be locally important. The oxygen decline rate is greater in coastal waters than in the open ocean (Gilbert et al., 2010). Hypoxia poses a serious threat to marine life, which is exacerbated when combined with elevated temperature (Vaquer-Sunyer and Duarte, 2011; see also Section 6.3.3). The number of so-called "dead zones" has approximately doubled each decade since 1960 (Diaz and Rosenberg, 2008). Fishery catches from these areas are generally lower than predicted from nutrient loading alone (Breitburg et al., 2009). Although non-climate anthropogenic factors are responsible for virtually all hypoxia in estuaries and inner continental shelves, climate drivers such as ocean warming, altered hydrological cycles, and coastal current shifts and changes in upwellings may interact with eutrophication in the next decades (Rabalais et al., 2010; Meire et al., 2013; *high confidence*).

5.3.4.4. Sediment Delivery

Human activities in drainage basins and coastal plains have impacted the coastal zone by changing the delivery of sediment to the coast. Sediment trapping behind dams, water diversion for irrigation, and sand and gravel mining in river channels all contribute to decrease sediment delivery, whereas soil erosion due to land use changes helps increase it (Syvitski, 2008; Walling, 2006). It is estimated that the global discharge of riverine sediment was 16 to 19 Gt yr^{-1} in the 1950s before widespread dam construction (e.g., Syvitski et al., 2005; Milliman and Farnsworth, 2011) and it has decreased to 12 to 13 Gt yr^{-1} (Syvitski and Kettner, 2011). Out of 145 major rivers with mostly more than 25 years of record, only seven showed evidence of an increase in sediment flux while 68 showed significant downward trends (Walling and Fang, 2003). The number of dams has increased continuously and their distribution has expanded globally. As of early 2011, the world has an estimated 16.7 million reservoirs larger than 0.01 ha (Lehner et al., 2011). Globally, 34 rivers with drainage basins of 19 million km^2 in total show a 75% reduction in sediment discharge over the past 50 years (Milliman and Farnsworth, 2011). Reservoir trapping of sediments is estimated globally as 3.6 Gt yr^{-1} to more than 5 Gt yr^{-1} (Syvitski et al., 2005; Milliman and Farnsworth,

2011; Walling, 2012). Human pressure is the main driver of the observed declining trend in sediment delivery to the coast (*high agreement*).

5.4. Impacts, Vulnerabilities, and Risks

5.4.1. Introduction

This subsection briefly introduces the diverse approaches and methods applied in the literature on coastal impact, vulnerability, and risk. The following subsections then assess this literature related to coastal natural systems (Section 5.4.2) and coastal human systems (Section 5.4.3). Much of this literature focuses on RSLR and extreme sea level events as the main drivers. The main biophysical impacts of this driver are increasing flood damage, dry-land loss due to submergence and erosion, wetland loss and change, saltwater intrusion into surface and ground water, and rising water tables and impeded drainage (Table 5-3).

Impacts and risks are assessed using a wide variety of approaches from the local to global scale. Sea level rise exposure approaches are applied at all scales to assess values exposed to sea level rise (e.g., people, assets, ecosystems, or geomorphological units). Submergence exposure approaches assess exposure to permanent inundation under a given sea level rise (e.g., Dasgupta et al., 2009; Boateng, 2012) whereas flood exposure approaches assess exposure to temporary inundation during a coastal flood event by combining the extreme water level of the flood event with a given level of sea level rise (e.g., Dasgupta et al., 2011; Kebede and Nicholls, 2012).

Indicator-based approaches are also used at all scales to aggregate data on the current state of the coastal systems into vulnerability indices (Gornitz, 1991; Hinkel, 2011), based on either biophysical exposure or hazard variables (e.g., Bosom and Jimenez, 2011; Yin et al., 2012), socioeconomic variables representing a social group's capacity to adapt (e.g., Cinner et al., 2012), or both kinds of variables (e.g., Bjarnadottir et al., 2011; Li and Li, 2011; Yoo et al., 2011).

At local scales (<100 km coastal length), process-based models are applied to assess flooding, erosion, and wetland impacts. Approaches include assessments of flood damage of single extreme water level events using numerical inundation models (e.g., Lewis et al., 2011; Xia et al., 2011). Erosion impacts are assessed using either numerical morphodynamic models (e.g., Jiménez et al., 2009; Ranasinghe et al., 2012) or simple geometric profile relationships such as the Bruun Rule (Bruun, 1962). For ecosystem impacts ecological landscape simulation models are used to predict habitat change due to sea level rise and other factors (e.g., Costanza et al., 1990).

At regional to global scales, numerical process-based models are not available for assessing the impacts of RSLR and extreme sea level events due to data and computational limits. Global scale assessments of coastal impacts have been conducted with the models Climate Framework for Uncertainty, Negotiation and Distribution (FUND) and Dynamic and Interactive Coastal Vulnerability Assessment (DIVA). FUND is an integrated assessment model with a coastal impact component that includes country-level cost functions for dry-land loss, wetland loss, forced migration, and dike construction (Tol, 2002). DIVA is a dedicated coastal impact model employing subnational coastal data (Vafeidis et al., 2008) and considering additional impacts such as coastal flooding and erosion as well as adaptation in terms of protection via dikes and nourishment (Hinkel and Klein, 2009). DIVA assesses coastal flood risk based on hydrologically connected elevation and extreme water level distributions

Frequently Asked Questions

FAQ 5.1 | How does climate change affect coastal marine ecosystems?

The major climate-related drivers on marine coastal ecosystems are sea level rise, ocean warming, and ocean acidification.

Rising sea level impacts marine ecosystems by drowning some plants and animals as well as by inducing changes of parameters such as available light, salinity, and temperature. The impact of sea level is related mostly to the capacity of animals (e.g., corals) and plants (e.g., mangroves) to keep up with the vertical rise of the sea. Mangroves and coastal wetlands can be sensitive to these shifts and could leak some of their stored compounds, adding to the atmospheric supply of these greenhouse gases.

Warmer temperatures have direct impacts on species adjusted to specific and sometimes narrow temperature ranges. They raise the metabolism of species exposed to the higher temperatures and can be fatal to those already living at the upper end of their temperature range. Warmer temperatures cause coral bleaching, which weakens those animals and makes them vulnerable to mortality. The geographical distribution of many species of marine plants and animals shifts towards the poles in response to warmer temperatures.

When atmospheric carbon dioxide is absorbed into the ocean, it reacts to produce carbonic acid, which increases the acidity of seawater and diminishes the amount of a key building block (carbonate) used by marine 'calcifiers' such as shellfish and corals to make their shells and skeletons and may ultimately weaken or dissolve them. Ocean acidification has a number of other impacts, many of which are still poorly understood.

Table 5-3 | Main impacts of relative sea level rise. Source: Adapted from Nicholls et al. (2010).

Biophysical impacts of relative sea level rise	Other climate-related drivers	Other human drivers
Dryland loss due to erosion	Sediment supply, wave and storm climate	Activities altering sediment supply (e.g., sand mining)
Dryland loss due to submergence	Wave and storm climate, morphological change, sediment supply	Sediment supply, flood management, morphological change, land claim
Wetland loss and change	Sediment supply, CO_2 fertilization	Sediment supply, migration space, direct destruction
Increased flood damage through extreme sea level events (storm surges, tropical cyclones, etc.)	Wave and storm climate, morphological change, sediment supply	Sediment supply, flood management, morphological change, land claim
Saltwater intrusion into surface waters (backwater effect)	Runoff	Catchment management and land use (e.g., sand mining and dretching)
Saltwater intrusion into groundwaters leading to rising water tables and impeded drainage	Precipitation	Land use, aquifer use

(Hinkel et al., 2013) and erosion based on a combination of the Bruun Rule and a simplified version of the Aggregated Scale Morphological Interaction between a Tidal inlet and the Adjacent coast (ASMITA) model for tidal basins (Nicholls et al., 2011). The results of these models are discussed in Sections 5.4.3.1 and 5.5.5.

For impacts on natural systems, the key climate-related drivers considered are temperature, ocean acidification, and sea level. A variety of approaches are applied including field observations of ecosystem features (e.g., biodiversity, reproduction) and functioning (e.g., calcification, primary production), remote sensing (e.g., extent of coral bleaching, surface area of vegetated habitats), and perturbation experiments in the laboratory and in the field.

5.4.2. Natural Systems

Coastal ecosystems are experiencing large cumulative impacts related to human activities (Halpern et al., 2008) arising from both land- and ocean-based anthropogenic drivers. Anthropogenic drivers associated with global climate change are distributed widely and are an important component of cumulative impacts experienced by coastal ecosystems. There is no wetland, mangrove, estuary, rocky shore, or coral reef that is not exhibiting some degree of impact. Overexploitation and habitat destruction are often the primary causes of historical changes in coastal systems leading to declines in diversity, structure, and functioning (Lotze et al., 2006). Further, extreme climate events generate changes to both the mean and the variance of climatic variables over ecological time scales.

5.4.2.1. Beaches, Barriers, and Sand Dunes

Beaches, barriers, and sand dunes are about half as common as rocky coasts (Bird, 2000; Davis and FitzGerald, 2004) and often exhibit distinct and seasonal changes. Owing to their aesthetic qualities, they are highly valued for recreation and residences.

5.4.2.1.1. Observed impacts

Globally, beaches and dunes have in general undergone net erosion over the past century or longer (e.g., for an overview, see Bird, 2000). A number of studies have investigated shoreline change by comparing historical maps and imagery, available since about the mid-19th century with more recent maps and imagery to quantify combined climate and non-climate changes. For example, along the U.S. Mid-Atlantic and New England coasts the long-term rate of erosion, based on 21,184 transects equally spaced along more than 1000 km of coast, is 0.5 ± 0.09 m yr^{-1}, with 65% of transects showing net erosion (Hapke et al., 2011). A similar study by Webb and Kench (2010) in the central Pacific utilized historical aerial photographs and satellite images to show physical changes in 27 islets located in four atolls over a 19- to 61-year period. The analysis highlighted the dynamic nature of sea level rise response in the recent past, with physical changes in shoreline progradation and displacement influencing whether the island area increased (46%), remained stable (46%), or decreased (14%).

Attributing shoreline changes to climate change is still difficult owing to the multiple natural and anthropogenic drivers contributing to coastal erosion. For example, rotation of pocket beaches (i.e., where one end of the beach accretes while the other erodes and then the pattern reverses) in southeast Australia is closely related to interannual changes in swell direction (Harley et al., 2010). Additional processes, unrelated to climate change, that contribute to coastal change include dams capturing fluvial sand (e.g., in Morocco; Chaibi and Sedrati, 2009). Statistically linking sea level rise to observed magnitudes of beach erosion has had some success, although the coastal sea level change signal is often small when compared to other processes (e.g., Leatherman et al., 2000a,b; Sallenger et al., 2000; Zhang et al., 2004). A Bayesian network incorporating a variety of factors affecting coastal change, including RSLR, has been successful in hindcasting shoreline change, and can be used to evaluate the probability of future shoreline change (Gutierrez et al., 2011).

While some coastal systems may be able to undergo landward retreat under rising sea levels, others will experience coastal squeeze, which occurs when an eroding shoreline approaches hard, immobile structures such as seawalls or resistant natural cliffs. In these instances the beaches will narrow owing to the resulting sediment deficit and produce adverse impacts such as habitat destruction, impacting the survivability of a variety of organisms (Jackson and McIlvenny, 2011). With such a manifestation of coastal squeeze, sand dunes will ultimately be removed as the beach erodes and narrows. Extreme storms can erode and completely remove dunes, degrading land elevations and exposing them to inundation and further change if recovery does not occur before the next storm (Plant et al., 2010). Even in the absence of hard obstructions, barrier island erosion and narrowing can occur, as a result of rising sea level and recurrent storms, as in the Chandeleur Islands and Isles Dernieres, Louisiana, USA (Penland et al., 2005).

5.4.2.1.2. Projected impacts

With projected GMSLR (see Section 5.3.3), inundation and erosion may become detectable and progressively important. In the first instance,

Frequently Asked Questions

FAQ 5.2 | How is climate change influencing coastal erosion?

Coastal erosion is influenced by many factors: sea level, currents, winds, and waves (especially during storms, which add energy to these effects). Erosion of river deltas is also influenced by precipitation patterns inland which change patterns of freshwater input, runoff, and sediment delivery from upstream. All of these components of coastal erosion are impacted by climate change.

Based on the simplest model, a rise in mean sea level usually causes the shoreline to recede inland due to coastal erosion. Increasing wave heights can cause coastal sand bars to move away from the shore and out to sea. High storm surges (sea levels raised by storm winds and atmospheric pressure) also tend to move coastal sand offshore. Higher waves and surges increase the probability that coastal sand barriers and dunes will be over-washed or breached. More energetic and/or frequent storms exacerbate all these effects.

Changes in wave direction caused by shifting climate may produce movement of sand and sediment to different places on the shore, changing subsequent patterns of erosion.

the impacts will be apparent through sea level rise which, combined with storm surge, will make extreme water levels higher and more frequent and therefore enable greater attack on beaches and dunes (Tebaldi et al., 2012).

The Bruun rule (a simple rule based on the assumption that to maintain an equilibrium cross-shore profile under rising sea levels, the coastline will move landwards a distance of approximately 100 times the vertical sea level rise; Bruun, 1962) has been used by many researchers to calculate erosion by sea level rise. However, there is disagreement about whether the Bruun rule is appropriate (Cooper and Pilkey, 2004; Woodroffe and Murray-Wallace, 2012), and how to calculate the amount of retreat remains controversial (Gutierrez et al., 2011; Ranasinghe et al., 2012). An increase in storm intensity and ocean swell may accelerate erosion of beaches, barriers, and dunes, although in some places beach response to sea level rise could be more complex than just a simple retreat (Irish et al., 2010).

Coastal squeeze is expected to accelerate with a rising sea level. In many locations, finding sufficient sand to rebuild beaches and dunes artificially will become increasingly difficult and expensive as present supplies near project sites are depleted (*high confidence*). New generation models are emerging to estimate the costs of saving oceanfront homes through beach nourishment relative to the structures cost (McNamara et al., 2011). In the absence of adaptation measures, beaches and sand dunes currently affected by erosion will continue to be affected under increasing sea levels (*high confidence*).

5.4.2.2. Rocky Coasts

Rocky coasts with shore platforms form about three-fourths of the world's coasts (Davis and FitzGerald, 2004; Jackson and McIlvenny, 2011) and are characterized by very strong environmental gradients, especially in the intertidal zone where both marine and atmospheric climate regime changes can pose challenges.

5.4.2.2.1. Observed impacts

Cliffs and platforms are erosional features and any change that increases the efficiency of processes acting on them, such as RSLR, storminess, wave energy, and weathering regimes, increases erosion (Naylor et al., 2010). Their responses vary, owing to different lithology (e.g., hard rock vs. non-lithified soft rock) and profiles (e.g., plunging cliffs or cliffs with shore platforms). Cliffs and platforms have reduced resilience to climate change impacts; once platforms are lowered or cliffs have retreated, it is difficult to rebuild them (Naylor et al., 2010). On the decadal scale, for example, the retreat of soft rock cliffs in East Anglia, UK, has been linked to the North Atlantic Oscillation (NAO) phases with high energetics (Brooks and Spencer, 2013).

Changes in the abundance and distribution of rocky shore animals and algae have long been recognized (Hawkins et al., 2008), and perturbation experiments provide information about environmental limits, acclimation, and adaptation, particularly to changes in temperature (Somero, 2012). The challenge is to attribute the changes to climate-related drivers, human-related drivers, and to natural fluctuations.

The range limits of many intertidal species have shifted by up to 50 km per decade over the past 30 years in the North Pacific and North Atlantic, much faster than most recorded shifts of terrestrial species (Helmuth et al., 2006; Box CC-MB). However, the distribution of some species has not changed in recent decades, which may be due to weak local warming (Rivadeneira and Fernández, 2005) or overriding effects of variables such as timing of low tide; hydrographic features; lack of suitable substrate; poor larval dispersal; and effects of food supply, predation, and competition (Helmuth et al., 2002, 2006; Poloczanska et al., 2011).

The dramatic decline of biodiversity in mussel beds of the Californian coast has been attributed to large-scale processes associated with climate-related drivers (59% mean loss in species richness, comparing 2002 to historical data (1960s to 1970s); Smith et al., 2006) (*high*

confidence). Warming reduced predator-free space on rocky shores, leading to a decrease of the vertical extent of mussel beds by 51% in 52 years in the Salish Sea, and to the disappearance of reproductive populations of mussels (Harley, 2011). Unusually high air or water temperature led to mass mortalities, for example, of mussels on the California coast (Harley, 2008) and gorgonians in the northwestern Mediterranean (Garrabou et al., 2009).

Rocky shores are one of the few ecosystems for which field evidence of the effects of ocean acidification is available. Observational and modeling analysis have shown that the community structure of a site of the northeast Pacific shifted from a mussel to an algal-barnacle dominated community between 2000 and 2008 (Wootton et al., 2008), in relation with rapidly declining pH (Wootton and Pfister, 2012).

5.4.2.2.2. Projected impacts

Modeled relationships suggest that soft-rock recession rates depends on the relative change in sea level rise while cliff retreat depends both on total elevation change of sea level and on the rate of sea level rise (Ashton et al., 2011). In a modeling study, Trenhaile (2010) found sea level rise to trigger faster rates of cliff recession, especially in coasts that are already retreating fast. In addition, based on modeling cliff dynamics with contemporary and historic data of soft cliff retreat along Suffolk Coast, UK, rapid retreat is associated with accelerating sea level rise (Brooks and Spencer, 2013). However, coasts currently retreating slowly would experience the largest proportional increase in retreat rates. Increases in storminess have smaller effects on rocky shores (Dawson et al., 2009; Trenhaile, 2011).

Few projections of the effect of climate change on rocky shores have considered the effects of direct and indirect species interactions (Poloczanska et al., 2008; Harley, 2011) and the effects of multiple drivers (Helmuth et al., 2006). The abundance and distribution of rocky shore species will continue to change in a warming world (*high confidence*). For example, the long-term consequences of ocean warming on mussel beds of the northeast Pacific are both positive (increased growth) and negative (increased susceptibility to stress and of exposure to predation) (Smith et al., 2006; Menge et al., 2008; *medium confidence*). Extrapolations of ecosystem change based on temperature-focused studies alone are likely to be conservative, as hypoxia (Grantham et al., 2004) or ocean acidification (Feely et al., 2008) are also known to occur in this region.

Observations performed near natural CO_2 vents in the Mediterranean Sea show that diversity, biomass, and trophic complexity of rocky shore communities will decrease at future pH levels (Barry et al., 2011; Kroeker et al., 2011; *high confidence*). An abundant food supply appears to enable mussels of the Baltic Sea to tolerate low pH (Thomsen et al., 2010, 2013) at the cost of increased energy expenditure. Model projections that include the interactive effects of ocean warming and acidification suggest that a population of barnacle of the English Channel will become extinct 10 years earlier than it would with warming alone (Findlay et al., 2010; *medium confidence*). Ocean acidification may also exacerbate mass mortality events in the Mediterranean Sea (Rodolfo-Metalpa et al., 2011; *limited evidence*, *medium agreement*).

In summary, rocky shores are among the better-understood coastal ecosystems in terms of potential impacts of climate variability and change. The most prominent effects are range shifts of species in response to ocean warming (*high confidence*) and changes in species distribution and abundance (*high confidence*) mostly in relation to ocean warming and acidification.

5.4.2.3. Wetlands and Seagrass Beds

Vegetated coastal habitats and coastal wetlands (mangrove forests, salt marshes, seagrass meadows, and macroalgal beds) extend from the intertidal to the subtidal areas in coastal areas, where they form key ecosystems.

5.4.2.3.1. Observed impacts

Vegetated coastal habitats are declining globally (Duarte et al., 2005), rendering shorelines more vulnerable to erosion due to increased sea level rise and increased wave action (e.g., Alongi, 2008) and leading to the loss of carbon stored in sediments. Together, the loss of coastal wetlands and seagrass meadows results in the release of 0.04 to 0.28 PgC annually from organic deposits (Pendleton et al., 2012). Recognition of the important consequences of the losses of these habitats for coastal protection and carbon burial (Duarte et al., 2013a) has led to large-scale reforestation efforts in some nations (e.g., Thailand, India, Vietnam).

The response of saltmarshes to sea level rise involves landward migration of salt-marsh vegetation zones, submergence at lower elevations, and drowning of interior marshes. Ocean warming is leading to range shifts in vegetated coastal habitats. The poleward limit of mangrove forests is generally set by the 20ºC mean winter isotherm (Duke et al., 1998). Accordingly, migration of the isotherm with climate change (Burrows et al., 2011) should lead to a poleward expansion of mangrove forests, as observed in the Gulf of Mexico (Perry and Mendelssohn, 2009; Comeaux et al., 2011; Raabe et al., 2012) and New Zealand (Stokes et al., 2010), leading to increased sediment accretion (*medium confidence*).

Seagrass meadows are already under stress due to climate change (*high confidence*), particularly where maximum temperatures already approach their physiological limit. Heat waves lead to widespread seagrass mortality, as documented for *Zostera* species in the Atlantic (Reusch et al., 2005) and *Posidonia* meadows in the Mediterranean Sea (Marbà and Duarte, 2010) and Australia (Rasheed and Unsworth, 2011; *high confidence*). Warming also favors flowering of *P. oceanica* (Diaz-Almela et al., 2007), but the increased recruitment rate is insufficient to compensate for the losses resulting from elevated temperatures (Diaz-Almela et al., 2009).

Kelp forests have been reported to decline in temperate areas in both hemispheres (Fernández, 2011; Johnson et al., 2011; Wernberg et al., 2011a,b), a loss involving climate change (*high confidence*). Decline in kelp populations attributed to ocean warming has been reported in southern Australia (Johnson et al., 2011; Wernberg et al., 2011a,b) and the North Coast of Spain (Fernández, 2011). The spread of subtropical invasive macroalgal species may be facilitated by climate change,

adding to the stresses experienced by temperate seagrass meadows due to ocean warming (*medium evidence*, *high agreement*).

5.4.2.3.2. Projected impacts

Ocean acidification (Section 5.3.3.5; Box CC-OA) is expected to enhance the production of seagrass, macroalgae, salt-marsh plants, and mangrove trees through the fertilization effect of CO_2 (Hemminga and Duarte, 2000; Wu et al., 2008; McKee et al., 2012; *high confidence*). Increased CO_2 concentrations may have already increased seagrass photosynthetic rates by 20% (Hemminga and Duarte, 2000; Hendriks et al., 2010; *limited evidence, high agreement*).

Coupling of downscaled model projections using the SRES A1B scenario in the western Mediterranean with relationships between mortality rates and maximum seawater temperature led Jordá et al. (2012) to conclude that seagrass meadows may become functionally extinct by 2050–2060 (*high confidence*). Poleward range shifts in vegetated coastal habitats are expected to continue with climate change (*high confidence*).

Although elevated CO_2 and ocean acidification are expected to increase productivity of vegetated coastal habitats in the future, there is *limited evidence* that elevated CO_2 will increase seagrass survival or resistance to warming (Alexandre et al., 2012; Jordá et al., 2012).

Coastal wetlands and seagrass meadows experience coastal squeeze in urbanized coastlines, with no opportunity to migrate inland with rising sea levels. However, increased CO_2 and warming can stimulate marsh elevation gain, counterbalancing moderate increases in sea level rise rates (Langley et al., 2009; Kirwan and Mudd, 2012). Climate change is expected to increase carbon burial rates on salt marshes during the first half of the 21st century, provided sufficient sediment supply, with carbon-climate feedbacks diminishing over time (Kirwan and Mudd, 2012; *medium confidence*).

In summary, climate change will contribute to the continued decline in the extent of seagrasses and kelps in the temperate zone (*medium confidence*) and the range of seagrasses, mangroves, and kelp in the Northern Hemisphere will expand poleward (*high confidence*). The limited positive impact of warming and increased CO_2 on vegetated ecosystems will be insufficient to compensate the decline of their extent resulting from other human drivers such as land use change (*very high confidence*).

5.4.2.4. Coral Reefs

Coral reefs are shallow-water ecosystems made of calcium carbonate secreted by reef-building corals and algae. They are among the most diverse ecosystems and provide key services to humans (Box CC-CR).

5.4.2.4.1. Observed impacts

Mass coral bleaching coincided with positive temperature anomalies over the past 30 years, sometimes followed by mass mortality (Kleypas et al., 2008; *very high confidence*). More than 80% of corals bleached during the 2005 event in the Caribbean and more than 40% died (Eakin et al., 2010). Bleaching events and their recovery are variable in time and space: 7% of the reef locations exhibited at least one bleaching between 1985 and 1994 compared to 38% in the 1995–2004 period, most of which occurred during the 1997–98 El Niño event (Figure 5-3). Recovery from the 1998 global bleaching event was generally variable in the Indian Ocean, absent in the western Atlantic, and no clear trends elsewhere (Baker et al., 2008). Warming has caused a poleward range expansion of some corals (Greenstein and Pandolfi, 2008; Yamano et al., 2011; *high confidence*).

Persistence of coral reefs depends on the balance between the production and erosion of calcium carbonate and on coral settlement, both of which are affected by ocean acidification (Section 5.3.3.5; Box CC-OA). Experimental data show that ocean acidification generally decreases calcification (Andersson et al., 2011; Kroeker et al., 2013) and promotes dissolution of calcium carbonate and bioerosion (Tribollet et al., 2009; Wisshak et al., 2012), leading to poorly cemented reefs (Manzello et al., 2008); it also negatively affects early life history stages, which could reduce the number of larval settlers (Albright, 2011).

Coral cover and calcification have decreased in recent decades (e.g., Gardner et al., 2003; De'ath et al., 2009, 2012; Manzello, 2010; Box CC-CR; *very high confidence*) but attribution to climate-related and human-related drivers is difficult. Globally, the primary climate-related driver appears to be ocean warming rather than ocean acidification, cyclonic activity, and changes in freshwater input (Cooper et al., 2012; De'ath et al., 2012; *medium confidence*). Sea level rise also controls reef growth but, within the uncertainties of past sea level rise and coral reef growth, most coral reefs seem to have kept pace with the recent sea level rise (Buddemeier and Smith, 1988; Brown et al., 2011).

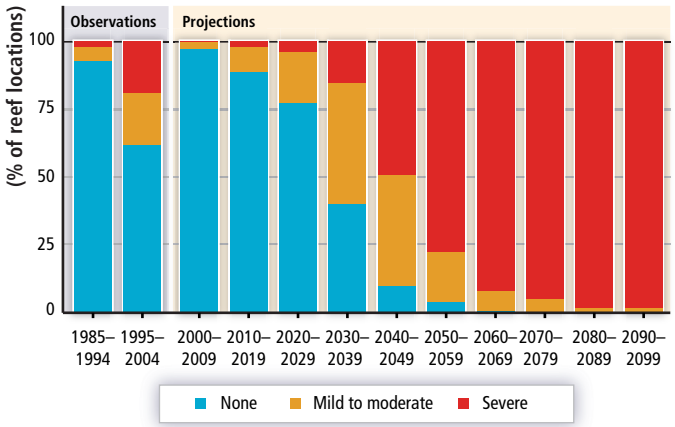

Figure 5-3 | Percent of reef locations (1° × 1° grid cells which have at least one reef) that experience no bleaching, at least one mild bleaching event, or at least one severe bleaching event for each decade. Observed bleaching events are summarized from the ReefBase data set (Kleypas et al., 2008). In the observations, some of the "no bleaching" cells may have experienced bleaching but it was either not observed or not reported. Modeled bleaching events are averages of data from four ensemble runs of the Community Climate System Model version 3 using the Special Report on Emissions Scenarios (SRES) A1B scenario and the standard degree heating month formula (Teneva et al., 2011). The labels of values ≤1% are not shown.

5.4.2.4.2. Projected impacts

Coral bleaching and mortality will increase in frequency and magnitude over the next decades (*very high confidence*). Under the A1B CO_2 emission scenario, 99% of the reef locations will experience at least one severe bleaching event between 2090 and 2099 (Figure 5-3), with *limited evidence* and *low agreement* that coral acclimation and/or adaptation will limit this trend (Logan et al., 2014). The onset of annual bleaching event under RCP8.5 is delayed by more than 2 decades in about 23% of reef locations compared to RCP6.0 (van Hooidonk et al., 2013).

Ocean warming and acidification have synergistic effects in several reef-builders (Reynaud et al., 2003; Anthony et al., 2008). They will increase coral mortality, reduce calcification and the strength of calcified organisms, and enhance skeletal dissolution (Manzello et al., 2008; *high confidence*). Reefs will transition from a condition of net accretion to one of net erosion (Andersson and Gledhill, 2013; *high confidence*) and will be more susceptible to breakage. The onset of global dissolution is at an atmospheric CO_2 of 560 ppm (Silverman et al., 2009; *medium confidence*) and dissolution will be widespread in 2100 (RCP8.5 emission scenario, Dove et al., 2013; *medium confidence*). The observed poleward range extension will be limited by ocean acidification (Yara et al., 2012; Couce et al., 2013) and may be followed by equatorial range retractions (Kiessling et al., 2012).

The maximum rate of vertical accretion has been variable regionally during the last deglaciation (about 20 mm yr^{-1}; Dullo, 2005; Montaggioni, 2005) and has not enabled all coral reefs to keep up with sea level rise. Some reefs kept up, even when the eustatic sea level rise exceeded 40 mm yr^{-1} (Camoin et al., 2012). A number of coral reefs could therefore keep up with the maximum rate of sea level rise of 15.1 mm yr^{-1} projected for the end of the century (WGI AR5 Table 13.5; *medium confidence*) but a lower net accretion than during the Holocene (Perry et al., 2013) and increased turbidity (Storlazzi et al., 2011) will weaken this capability (*very high confidence*).

In summary, ocean warming is the primary cause of mass coral bleaching and mortality (*very high confidence*), which, together with ocean acidification, deteriorates the balance between coral reef construction and erosion (*high confidence*). The magnitude of these effects depends on future rates of warming and acidification (*very high confidence*), with a limited moderating role owing to biological acclimation and adaptation (*medium confidence*).

5.4.2.5. Coastal Aquifers

Coastal aquifers are of strategic importance for the water supply of highly populated coastal areas, especially in small islands (Section 29.3).

5.4.2.5.1. Observed impacts

Temperature and evaporation rise, precipitation changes, and extended droughts affecting aquifer recharge can contribute to saltwater intrusion (Section 3.2.4). Rising sea levels and overwash from waves or storm surge are also relevant, especially in low-lying areas and islands (Terry and Falkland, 2010; White and Falkland, 2010; see also Section 29.3).

Aquifers on the coasts of the USA have experienced increased levels of salinity largely due to excessive water extraction (Barlow and Reichard, 2010). Natural drivers combined with over-extraction, pollution, mining, and erosion compound groundwater supply problems in small islands in the Pacific, Indian, and Atlantic Oceans (White et al., 2007; White and Falkland, 2010). This increased usage of groundwater resources globally has, over the last century, led to a reduction in groundwater quality, including increased salinization (*very high confidence*).

Attribution of saline intrusion to incremental sea level rise is still not sufficiently supported (Rozell and Wong, 2010; White and Falkland 2010). In small islands, observed saltwater intrusion due to flooding and overwash under storm events cannot be attributed to climate change (Section 29.3.2; *limited evidence*, *high agreement*).

5.4.2.5.2. Projected impacts

Available information on projected impacts on coastal aquifers is limited (Section 3.4.6). Rozell and Wong (2010) assessed the impact of rising sea levels on fresh water resources on Shelter Island (USA) for two different combinations of precipitation change and sea level rise. Projected impacts were highly dependent on local conditions. Ferguson and Gleeson (2012) concluded that the direct impact of groundwater extraction in the USA has been and will be much more significant than the impact of a 0.59 m sea level rise by the end of the 21st century under a wide range of hydrogeological conditions and population densities.

Saltwater intrusion is generally a very slow process; as a consequence, reaching equilibrium may take several centuries limiting the reversibility of the process in the near term (Webb and Howard, 2011).

Human-induced pressure will continue to be the main driver for aquifer salinization during the next century (*high confidence*). Changing precipitation, increased storminess, and sea level rise will exacerbate these problems (*limited evidence*, *high agreement*).

5.4.2.6. Estuaries and Lagoons

Coastal lagoons are shallow water bodies separated from the ocean by a barrier and connected at least intermittently to the ocean, while estuaries, where fresh and saltwater mix, are the primary conduit for nutrients, particulates, and organisms from land to the sea.

5.4.2.6.1. Observed impacts

Sediment accumulation in estuaries is high, heterogeneous, and habitat-specific and directly affected by human drivers, such as dredging and canalization, and indirectly via habitat loss, changes in sea level, storminess, and freshwater and sediment supply by rivers (Syvitski et al., 2005; Swanson and Wilson, 2008). Coastal lagoons are also susceptible to alterations of sediment input and erosional processes driven by changes

in sea level, precipitation, and storminess (Pickey and Young, 2009). Droughts, floods, and sea level rise impact estuarine circulation, tidal characteristics, suspended matter, and hence turbidity with consequences for biological communities, particularly in microtidal systems. Climate change and habitat modification (e.g., dams and obstructions) impact fish species such as salmon and eels that pass through estuaries (Lassalle and Rochard, 2009).

Enhanced nutrient delivery (Section 5.3.4.3) has resulted in major changes in biogeochemical processes, community structure, metabolic balance, and CO_2 exchange (Howarth et al., 2011; Canuel et al., 2012; Statham, 2012), including enhanced primary production which has affected coastal fishery yield (Nixon, 1982; Savage et al., 2012). Eutrophication has modified the food-web structure (*high confidence*) and led to more intense and long lasting hypoxia (Section 5.3.4.4), more frequent occurrence of harmful algal blooms (Breitburg et al., 2009; Howarth et al., 2011; *medium confidence*), and to enhanced emission of nitrous oxide (de Bie et al., 2002; Kroeze et al., 2010; *high confidence*).

In summary, there is *very high confidence* that humans have impacted lagoons and estuaries.

5.4.2.6.2. Projected impacts

The increase of atmospheric CO_2 levels will reduce the efflux of CO_2 from estuaries (Borges, 2005; Chen and Borges, 2009; *high confidence*). Its impact on the pH of estuarine and lagoon waters will generally be limited because other drivers are usually more important (Section 5.3.3.4 and Box CC-OA; *high confidence*). For example, freshwater flow in the Scheldt estuary was the main factor controlling pH, directly via a decreased supply of dissolved inorganic carbon and total alkalinity, and, indirectly, via decreased input ammonia loadings and lower rates of nitrification (Hofmann et al., 2009).

Changes in sea level and hydrology could affect lagoons and estuaries in multiple ways. Sea level rise will impact sediment redistribution, the partitioning of habitats within estuaries, salinity, tidal range, and submergence periods (Anthony et al., 2009; *high confidence*). Lagoons may shrink because landward migration is restricted due to human occupation or extend due to the drowning of marshes (Anthony et al., 2009; Pilkey and Young, 2009; Stutz and Pilkey, 2011). Salinity, primary production, biodiversity, fisheries, and aquaculture may be impacted by changes in water discharge, withdrawals and precipitation-evaporation balance (Webster and Harris, 2004; Smith et al., 2005; Anthony et al., 2009; Canu et al., 2010). Altered riverine discharge and warming may lead to enhanced thermal and/or salinity stratification of estuaries and lagoons. This has consequences for biogeochemical processes, organism distribution patterns, and frequency and duration of hypoxia (Diaz and Rosenberg, 2008; Rabalais et al., 2009; Hong and Shen, 2012; *medium confidence*). Stronger winds and droughts may reduce the extent, duration, and frequency of estuarine stratification, counteracting the decrease in oxygen concentration (Rabalais et al., 2009; *medium confidence*).

Changes in storm events may also alter the sediment deposition-erosion balance of lagoons and estuaries (Pilkey and Young, 2009), the structure and functioning of biological communities via the transport of communities and/or of their resources, and the underwater light climate (Wetz and Paerl, 2008; Canuel et al., 2012; *medium confidence*). Changes in precipitation extremes and freshwater supply may induce fluctuations in salinity with the associated adverse impacts on biodiversity, benthic macrofauna, and ecosystem functions (Jeppesen et al., 2007; Fujii and Raffaelli, 2008; Levinton et al., 2011; Pollack et al., 2011). Warming may directly affect most biological processes and the trophic status of coastal ecosystems, and higher carbon dioxide emission (Canuel et al., 2012; *limited evidence*, *medium agreement*). Warming may lengthen the duration of phytoplankton production season (Cloern and Jassby, 2008; *medium confidence*).

Any change in the primary production of lagoons might impact fisheries, as primary production and fisheries yield are correlated (Nixon, 1982; *limited evidence*, *medium agreement*). For example, seawater warming and changes in seasonal patterns of precipitations projected in the Venice lagoon, using the SRES A2 emission scenario for the period 2071–2100, may lead to a reduction in plankton production, with a decline of habitat suitability for clam growth and aquaculture (Canu et al., 2010).

Finally, projected changes in climate-related drivers such as warming, storms, sea level, and runoff will interact with non-climate human drivers (e.g., eutrophication, damming) and will have consequences for ecosystem functioning and services of lagoons and estuaries (*high confidence*).

In summary, the primary drivers of change in lagoons and estuaries are human-related rather than climate-related drivers (*very high confidence*). Future changes in climate-related drivers such as warming, acidification, waves, storms, sea level, and runoff will have consequences on the functions and services of ecosystems in lagoons and estuaries (*high confidence*) but the impacts cannot be assessed at the global scale as the key drivers operate at a local to regional scale.

5.4.2.7. Deltas

Characterized by the interplay between rivers, lands, and oceans and influenced by a combination of river, tidal, and wave processes, deltas are coastal complexes that combine natural systems in diverse habitats (e.g., tidal flats, salt marshes, mangroves, beaches, estuaries, low-lying wetlands) and human systems (e.g., houses, agriculture, aquaculture, industry, and transport). They are low-lying coastal landforms formed by riverine sediments in the areas around river mouths, mostly during the last 6000–8000 years of relatively stable sea level and have a population density more than 10 times the world average (Ericson et al., 2006; Foufoula-Georgiou et al., 2011). As low-lying plains, deltas are highly sensitive to changes in sea level. They are subject to climatic impacts from rivers upstream (e.g., freshwater input) and oceans downstream (e.g., sea level changes, waves) as well as within the deltas themselves. At the same time, they are affected by human activities such as land use changes, dam construction, irrigation, mining, extraction of subsurface resources, and urbanization (Nicholls et al., 2007).

5.4.2.7.1. Observed impacts

The combined impact of sediment reduction, RSLR, and land use changes in delta and river management on channels and banks has led to the

widespread degradation of deltas (*very high confidence*). The changes of sediment delivery from rivers due to dams, irrigation, and embankments/dikes create an imbalance in sediment budget in the coastal zones. Degradation of beaches, mangroves, tidal flats, and subaqueous delta fronts along deltaic coasts has been reported in many deltas (e.g., Nile and Ebro; Sanchez-Arcilla et al., 1998; Po, Simeoni and Corbau, 2009; Krishna-Godavari, Nageswara Rao et al., 2010; Changjiang, Yang et al., 2011; Huanghe, Chu et al., 1996; *very high confidence*). Deltaic coasts naturally evolve by seaward migration of the shoreline, forming a delta plain. However, decreasing sediment discharge during the last 50 years has decreased the growth of deltaic land, even reversing it in some locations (e.g., Nile, Godavari, Huanghe). Artificial reinforcement of natural levees also has reduced the inter-distributory basin sedimentation in most deltas, resulting in wetland loss.

The major impacts of sea level rise are changes in coastal wetlands, increased coastal flooding, increased coastal erosion, and saltwater intrusion into estuaries and deltas (Mcleod et al., 2010), which are exacerbated by increased human-induced drivers (*very high confidence*). Ground subsidence amplifies these hazards in farms and cities on deltaic plains through RSLR (Day and Giosan, 2008; Mazzotti et al., 2009). RSLR due to subsidence has induced wetland loss and shoreline retreat (e.g., the Mississippi delta; Morton et al., 2005; Chao Phraya delta, Saito et al., 2007; *high confidence*). Episodic events superimpose their effects on these underlying impacts and accelerate land loss (*high confidence*) (e.g., Hurricanes Katrina and Rita in 2005; Barras et al., 2008). To forestall submergence and frequent flooding, many delta cities now depend on a substantial infrastructure for flood defense and water management (Nicholls et al., 2010).

Deltas are impacted by river floods and oceanic storm surges (*very high confidence*). Tropical cyclones are noteworthy for their damages to deltas, for example, the Mississippi delta by Hurricane Katrina in 2005 (Barras et al., 2008), the Irrawaddy delta by Cyclone Nargis in 2008, and the Ganges-Brahmaputra delta by Cyclone Gorky in 1991 and Cyclone Sidr in 2007 (Murray et al., 2012; see also Box CC-TC). A detailed study of 33 deltas around the world found that 85% of them had experienced severe flooding in the past decade, causing the temporary submergence of 260,000 km^2 (Syvitski et al., 2009).

5.4.2.7.2. Projected impacts

The projected natural impacts on deltas under changing global climate are caused mainly by extreme precipitation-induced floods and sea level rise. These will result in increased coastal flooding, decreased wetland areas, increased coastal erosion, and increased salinization of cultivated land and groundwater (McLeod et al., 2010; Day et al., 2011; Box CC-TC; *high confidence*). The surface area of flooding in 33 deltas around the world is estimated to increase by 50% under sea level rise estimations as projected for 2100 by the IPCC AR4 (Syvitski et al., 2009). Non-climatic drivers (e.g., reduction in sediment delivery, subsidence, and land use changes) rather than climatic drivers have affected deltas for the last 50 years (Syvitski, 2008; *very high confidence*). Densely populated deltas are particularly vulnerable owing to further population growth together with the above-described impacts. The impacts beyond 2100 show a more complex and enhanced flood risk on deltas (e.g., Katsman et al., 2011).

In summary, increased human drivers have been primary causes in changes of deltas (e.g., land use, subsidence, coastal erosion) for at least the last 50 years (*very high confidence*). There is *high agreement* that future sea level rise will exacerbate the problems of increased anthropogenic degradation in deltas.

5.4.3. Human Systems

5.4.3.1. Human Settlements

Important direct effects of climate change on coastal settlements include dry-land loss due to erosion and submergence, damage of extreme events (such as wind storms, storm surges, floods, heat extremes, and droughts) on built environments, effects on health (food- and water-borne disease), effects on energy use, effects on water availability and resources, and loss of cultural heritage (Hunt and Watkiss, 2010). Since AR4, a large number of regional, national, and subnational scale studies on coastal impacts have been conducted. These are covered in the respective regional chapters. At the global scale, studies have focused either on exposure to sea level rise or extreme water levels or on the physical impacts of flooding, submergence, and erosion.

5.4.3.1.1. Projected exposure

Coastal flood risks are strongly influenced by the growing exposure of population and assets. The population exposed to the 1-in-100-year coastal flood is projected to increase from about 270 million in 2010 to 350 million in 2050 due to socioeconomic development only (UN medium fertility projections) (Jongman et al., 2012). Population growth, economic growth, and urbanization will be the most important drivers of increased exposure in densely populated areas (Hanson et al., 2011; Seto, 2011; see also Chapter 14; *high confidence*). For 136 port cities above 1 million inhabitants, the number of people exposed to a 1-in-100-year extreme sea level is expected to increase from 39 million in 2005 to 59 million by 2070 through 0.5 m GMSLR alone and to 148 million if socioeconomic development (UN medium population projections) is considered (Hanson et al., 2011). Human-induced subsidence alone is expected to increase the global economic exposure of 136 major port cities by around 14% from 2005 to 2070 although this driver only applies to 36 of the cities (Hanson et al., 2011). As a result of socioeconomic development Asia is expected to continue to have the largest exposed population and sub-Saharan Africa the largest increases in exposure (Dasgupta et al., 2009; Vafeidis et al., 2011; Jongman et al., 2012).

5.4.3.1.2. Projected impacts and risks

Exposure estimates, however, give an incomplete picture of coastal risks to human settlements because they do not consider existing or future adaptation measures that protect the exposed population and assets against coastal hazards (Hallegatte et al., 2013; Hinkel et al., 2013). Although the global potential impacts of coastal flood damage and land loss on human settlements in the 21st century are substantial, these impacts can be reduced considerably through coastal protection (*limited evidence*, *high agreement*). Nicholls et al. (2011) estimate that without



Figure 5-4 | The 20 coastal cities where average annual losses (AALs) increase most (in relative terms in 2050 compared with 2005) in the case of optimistic sea level rise, if adaptation maintains only current defense standards or flood probability (PD) (Hallegatte et al., 2013).

protection 72 to 187 million people would be displaced due to land loss due to submergence and erosion by 2100 assuming GMSLRs of 0.5 to 2.0 m by 2100. Upgrading coastal defenses and nourishing beaches would reduce these impacts roughly by three orders of magnitude. Hinkel et al. (2013) estimate the number of people flooded annually in 2100 to reach 117 to 262 million per year in 2100 without upgrading protection and two orders of magnitude smaller with dike (levee) upgrades, given GMSLRs of 0.6 to 1.3 m by 2100. The major driver of increasing risks to human settlements in the next decades is socioeconomic development. When upgrading flood defenses to maintain a constant probability of flooding, average annual losses (AALs) in the 136 largest coastal cities are expected to increase ninefold from 2005 to 2050 due to socioeconomic development, only another 12% due to subsidence, and 2 to 8% due to GMSLRs of 0.2 to 0.4 m (Hallegate et al., 2013; Figure 5-4).

Despite the delayed response of sea level rise to global warming levels (WGI AR5 Section 13.5.4) mitigation may limit 21st century impacts of increased coastal flood damage, dry-land loss, and wetland loss substantially (*limited evidence*, *medium agreement*) albeit numbers are difficult to compare owing to differences in scenarios, baselines, and adaptation assumptions. Tol (2007) finds that stabilizing CO_2 concentration at 550 ppm reduces global impacts on wetlands and dry lands by about 10% in 2100 compared to a scenario of unmitigated emissions. Hinkel et al. (2013) report that stabilizing emissions at 450 ppm CO_2-eq reduces the average number of people flooded in 2100 by about 30% compared to a baseline where emissions increase to about 25 Gt C-eq in 2100. Arnell et al. (2013) find that an emissions pathway peaking in 2016 and declining at 5% per year thereafter reduces flood risk by 58 to 66% compared to an unmitigated A1B scenario. All three studies only consider the effects of mitigation during the 21st century and assume low or no contribution of ice sheets to GMSLR. Mitigation is expected to be more effective when considering impacts beyond 2100 and higher contributions of ice sheets (Section 5.5.8).

Global studies confirm AR4 findings that there are substantial regional differences in coastal vulnerability and expected impacts (*high confidence*). Most countries in South, Southeast, and East Asia are particularly vulnerable to sea level rise due to rapid economic growth and coastward migration of people into urban coastal areas together with high rates of anthropogenic subsidence in deltas where many of the densely populated areas are located (Nicholls and Cazenave, 2010). At the same time, economic growth in these countries increases the monetary capacity to adapt (Nicholls et al., 2010). In contrast, although many African countries experience a similar trend in rapid urban coastal growth, the level of economic development is generally lower and consequently the monetary capacity to adapt is smaller (Kebede and Nicholls, 2012; Hinkel et al., 2013).

In summary, while there is *high agreement* on some general findings, only a small fraction of the underlying uncertainty has been explored, which means evidence is limited. Gaps remain with respect to impacts of possible large contributions of the ice sheets of Greenland and Antarctica to GMSLR (WGI AR5 Sections 13.4.3, 13.4.4), regional patterns of climate-induced sea level rise, subsidence, and socioeconomic change and migration. Many studies rely on few or only a single socioeconomic scenario. Few studies consider adaptation and those that do generally ignore the wider range of adaptation measures beyond hard protection

options. Integrated studies considering the interactions between a wide range of RSLR impacts (Table 5-3) as well as trade-offs between diverse adaptation options are missing.

5.4.3.2. Industry, Infrastructure, Transport, and Network Industries

Coastal industries, their supporting infrastructure including transport (ports, roads, rail, airports), power and water supply, storm water, and sewerage are highly sensitive to a range of extreme weather and climate events including temporary and permanent flooding arising from extreme precipitation, high winds, storm surges, and sea level rise (Horton et al. 2010; Handmer et al. 2012; Hanson and Nicholls, 2012; Aerts et al. 2013; *high confidence*). Most industrial facilities, infrastructure, and networks are designed for service lives extending over several decades. In fact, many bridges, ports, and road and railway lines remain in their original design location for centuries even if the infrastructure on them has been rehabilitated or replaced several times. Certain facilities, such as new nuclear power plants, are designed to last even well beyond the 22nd century (Wilby et al., 2011).

As the need to locate most of these industries and networks in coastal areas will remain and probably increase due to coastal development (Section 5.4.3.1), considering climate variability and climate change drivers in life cycle assessment of industry, infrastructure, and transport and network industries is of utmost importance (*high confidence*).

5.4.3.2.1. Observed impacts

Climate impacts on coastal industries and infrastructures vary considerably depending on geographical location, associated weather and climate, and specific composition of industries within particular coastal regions (*high confidence*).

Over the last 10 years an extensive number of climate-related extreme events (Coumou and Rahmstorf, 2012) illustrate the potential for impacts on coastal industry, infrastructure, transport, and network industry. Severe storms with associated winds, waves, rain, lightning, and storm surges have been particularly disruptive to transport and power and water supplies (Jacob et al., 2007; USCCSP, 2008; Horton et al., 2010; *high confidence*). In such network configurations, flooding of even the smallest component of an intermodal system can result in a much larger system disruption. Even though a transportation terminal may not be affected, the access roads to it could be, thus forcing the terminal to cease or reduce operation. Disruption to port activities in one location can disrupt supply chains, which can have far reaching consequences (Becker et al. 2012, 2013). Existing experience has also shown that impacts of hurricanes and flooding on underground infrastructure can have long-term effects (Chisolm and Matthews, 2012).

Hurricanes like Katrina (2005) caused US$100 million of damage to Mississippi's ports and Sandy (2012) led to a week-long shut-down of the Port of New York, generating economic damages reaching US$50 billion (Becker et al., 2012). These have shown the critical need to better prepare coastal human settlements and associated network infrastructures and industries for future extreme weather impacts and climate change (Aerts et al., 2013; *high confidence*).

5.4.3.2.2. Projected impacts

Although there is *robust evidence* of the impacts and consequences of extreme events on coastal infrastructure and industrial facilities, there are limited assessments on projected impacts of long-term changes (*high agreement*). Besides, while there is an important amount of non-journal literature on projected impacts of sea level rise and increasing flooding levels on certain coastal infrastructures (USCCSP, 2008; USACE, 2011; McEvoy and Mullet, 2013), limited peer review information is available.

Vulnerability to flooding of railroads, tunnels, ports, roads, and industrial facilities at low-lying areas will be exacerbated by rising sea levels or more frequent or intense storms, causing more frequent and more serious disruption of services and damages under extreme sea levels unless adaptation is enforced (Esteban et al., 2010, 2012; Wilby et al., 2011; Aerts et al., 2013; *high confidence*).

Furthermore, sea level rise will reduce extreme flood return periods and therefore increase the need for adaptation of infrastructure such as airports, tunnels, coastal protections, and ship terminals to extreme sea level impacts (Jacob et al., 2007; Becker et al., 2013).

It is estimated that a hypothetical 1 m RSLR projected for the Gulf Coast region between Alabama and Houston over the next 50 to 100 years would permanently flood a third of the region's roads as well as putting more than 70% of the region's ports at risk (USCCSP, 2008).

The estimated costs of climate change to Alaska's public infrastructure could add US$3.6 to 6.1 billion (+10 to 20% above normal wear and tear) from now to 2030 and US$5.6 to 7.6 billion (+10 to 12%) from now to 2080 (Larsen et al., 2008). Higher costs of climate change for coastal infrastructure are expected due to its proximity to the marine environment. Other projected impacts are beneficial for the transportation system. For example, decline of Arctic sea-ice coverage could extend seasonal accessibility to high-latitude shipping routes such as the northwest shipping route that connects the Atlantic to the North Pacific.

Hanson et al. (2011) presents a first estimate of the exposure of the world's large port cities to coastal flooding due to sea level rise and storm surge in the 2070s. The analysis suggests that the total value of assets exposed in 2005 across all cities considered is estimated to be US$3000 billion, corresponding to around 5% of global GDP in 2005. By the 2070s, and assuming a homogeneous global sea level rise of 0.5 m, increased extreme water levels up to 10%, and a fixed subsidence rate in susceptible cities with respect to today's values, asset exposure is estimated to increase to approximately 9% of projected global GDP in this period.

Coastal infrastructural instability may result from natural hazards triggered by groundwater-level (GWL) variations resulting from rising sea level. For earthquake-prone coasts, this could be exacerbated by earthquake liquefaction if GWL increases with sea level rise (Yasuhara

et al., 2007). Increasing sea levels, surges, and waves can also lead to a stability loss of coastal structures (Headland et al., 2011).

Other impacts may arise in coastal industries in high latitudes affected by permafrost thaw causing ground instability and erosion, thereby affecting transport safety and the industries that rely on such travel in these regions (e.g., Pearce et al., 2010).

5.4.3.3. Fisheries, Aquaculture, and Agriculture

Fisheries and aquaculture and the associated post-harvest activities globally create millions of jobs (Daw et al., 2009; Sumaila et al., 2011) and contribute significantly to the dietary animal protein of millions of people and to the world merchandise trade (FAO, 2010, 2012; see also Section 6.4.1.1). In addition to small-scale fisheries and aquaculture, which are important for the food security and economy of coastal communities (Bell et al., 2009), coastal zones also support significant agricultural activities, for example, rice production in the low-lying deltaic regions of Asia (Wassmann et al., 2009).

5.4.3.3.1. Observed impacts

Climate variability and change impact both fishers' livelihoods (Badjeck et al., 2010) and fish production (Barange and Perry, 2009) (Section 6.5.3). In the North Sea, ocean warming over the 1977–2002 period led to relatively increased distribution ranges of some fish species (Hiddink and Hofstede, 2008), and demersal fish assemblage deepened in response to climate change (Dulvy et al., 2008). In southeastern Australia, Last et al. (2011) found an increasing abundance of 45 fish species of warm temperate origin, which they linked to the observed strengthening of the East Australian Current (EAC) bringing warm waters further south (Ridgeway, 2007). A study (Sherman et al., 2009) of the impact of sea surface temperature changes on the fisheries yields of 63 large marine ecosystems over a 25-year period shows a positive relationship for the northeast Atlantic large marine ecosystems, due to zooplankton biomass increases (Section 6.5.3). Distributional effects are very important for migratory pelagic fisheries, such as tuna (see Table 29-2). Impacts of climate change on aquaculture (*Mytilus edulis* and *Salmo salar*) in the UK and Ireland have been difficult to discern from natural environmental variability (Callaway et al., 2012).

Seawater inundation has become a major problem for traditional agriculture in Bangladesh (Rahman et al., 2009), and in low-lying island nations (e.g., Lata and Nunn, 2012). The combination of rice yield reduction induced by climate change and inundation of lands by seawater causes an important reduction in production (Chen et al., 2012).

5.4.3.3.2. Projected impacts

Fisheries may be impacted either negatively or positively (Hare et al., 2010; Meynecke and Lee, 2011; Cinner et al., 2012) depending on the latitude, location, and climatic factors. Climate change can impact the pattern of marine biodiversity through changes in species' distributions, and may lead to large-scale redistribution of global catch potential depending on regions (Cheung et al., 2009, 2010). Narita et al. (2012) estimated that the global economic costs of production loss of molluscs due to ocean acidification (Section 5.3.3.5) by the year 2100 based on IPCC IS92a business-as-usual scenario could be higher than US$100 billion. As a result of increased sea temperatures, the reduction in coral cover in the Caribbean basin and its associated fisheries production is expected to lead to a net revenue loss by 2015 (Trotman et al., 2009). Economic losses in landed catch value and the costs of adapting fisheries resulting from a 2°C global temperature increase by 2050 have been estimated at US$10 to 31 billion globally (Sumaila et al., 2011). For aquaculture, negative impacts of rising ocean temperatures will be felt in the temperate regions whereas positive impacts will be felt in the tropical and subtropical regions (De Silva and Soto, 2009). Changes to the atmosphere-ocean in the Pacific Island countries are likely to affect coral reef fisheries by a decrease of 20% by 2050 and coastal aquaculture may be less efficient (Bell et al., 2013).

In summary, changes have occurred to the distribution of fish species (*medium confidence*) with evidence of poleward expansion of temperate species (*limited evidence*, *high agreement*). Tropical and subtropical aquaculture has not been adversely affected by rising ocean temperatures to date (*limited evidence*, *high agreement*). Coastal agriculture has experienced negative impacts (*medium confidence*) due mainly to increased frequency of submersion of agricultural land by saltwater inundation (*limited evidence*, *high agreement*).

5.4.3.4. Coastal Tourism and Recreation

Coastal tourism is the largest component of the global tourism industry. Over 60% of Europeans opt for beach holidays and beach tourism provides more than 80% of U.S. tourism receipts (UNEP, 2009). More than 100 countries benefit from the recreational value provided by their coral reefs, which contributed US$11.5 billion to global tourism (Burke et al., 2011).

5.4.3.4.1. Observed impacts

Observed significant impacts on coastal tourism have occurred from direct impacts of extreme events on tourist infrastructure (e.g., beach resorts, roads), indirect impacts of extreme events (e.g., coastal erosion, coral bleaching), and short-term adverse tourist perception after the occurrence of extreme events (e.g., flooding, tropical storms, storm surges) (Phillips and Jones, 2006; Scott et al., 2008; IPCC, 2012, Section 4.3.5.3). Recent observed climate change impacts on the Great Barrier Reef include coral bleaching in the summers of 1997–1998, 2001–2002, and 2005–2006 and extreme events including floods and cyclones (Tropical cyclones Larry in 2006, Hamish in 2009, and Yasi in 2011). The stakeholders show a high level of concern for climate change, and various resilience initiatives have been proposed and developed by the Great Barrier Reef Marine Park Authority (Biggs, 2011; GBRMPA, 2012).

5.4.3.4.1. Projected impacts

To provide some idea of climate change impacts on coastal destinations, many studies have been carried out on projecting tourism demand, for

example, in Europe (Perch-Nielson et al., 2010), in the Baltic region (Haller et al., 2011), in the Mediterranean (Moreno and Amelung, 2009a), and in 51 countries worldwide (Perch-Nielson, 2010). The studies provide varying details, although it is difficult to draw overarching conclusions on tourism demand for coastal destinations. With increased temperature in mid-latitude countries and coupled with increased storms in tropical areas, tourist flows could decrease from mid-latitude countries to tropical coastal regions with large developing countries and small island nations most affected (Perch-Nielson, 2010). The Mediterranean would likewise be affected in summer (Moreno and Amelung, 2009a). In contrast, less is known about the relationship between the impacts of climate change and specific tourist behavior, activities, or flows to coastal destinations (Moreno and Amelung, 2009b; see Section10.6.2). Usually tourists do not consider climate variability or climate change in their holidays (Hares et al., 2009) although there are a few studies that show the contrary (Cambers, 2009; Alvarez-Diaz et al., 2010).

As for future impacts on coastal tourism, there is *high confidence* in the impacts of extreme events and sea level rise aggravating coastal erosion. A scenario of 1-m sea level rise by 2100 would be a potential risk to Caribbean tourism (Scott et al., 2012). The presence of coastal tourism infrastructure will continue to exacerbate beach reduction and coastal ecosystems squeeze under rising sea levels, as exemplified in Martinique (Schleupner, 2008). Carbonate reef structures would degrade under a scenario of at least 2°C by 2050–2100 with serious consequences for tourism destinations in Australia, the Caribbean, and other small islands (Hoegh-Gulberg et al., 2007; see Box CC-CR).

The costs of future climate change impacts on coastal tourism are enormous. For example, in the Caribbean community countries, rebuilding costs of tourist resorts are estimated US$10 to 23.3 billion in 2050. A hypothetical 1-m sea level rise would result in the loss or damage of 21 airports, inundation of land surrounding 35 ports, and at least 149 multi-million dollar tourism resorts damaged or lost from erosion to the coastal beach areas (Simpson et al., 2010).

In summary, while coastal tourism can be related to climate change impacts, it is more difficult to relate tourism demand directly to climate change. Coastal tourism continues to be highly vulnerable to weather, climate extremes, and rising sea levels with the additional sensitivity to ocean temperature and acidity for the sectors that rely on reef tourism (*high confidence*). Developing countries and small island states within the tropics relying on coastal tourism are most vulnerable to present and future weather and climate extremes, future sea level rise, and the added impacts of coral bleaching and ocean acidification (*high confidence*).

5.4.3.5. Health

The relationship between health of coastal populations and climate change include direct linkages (e.g., floods, droughts, storm surges, and extreme temperatures) and indirect linkages (e.g., changes in the transmission of vector-, food-, and water-borne infectious diseases and increased salinization of coastal land that affects food production and freshwater supply and ecosystem health). Coastal and particularly informal settlements concentrate injury risk and death from storm surges and rainfall flooding (Handmer et al., 2012). This section deals with human health in the context of the coastal zone, while Chapter 11 addresses general health issues and Section 6.4.2.3 deals with health issues associated with ocean changes. Understanding the relationship between climate and health is often confounded by socioeconomic factors that influence coastal settlement patterns and the capacity of authorities to respond to health-related issues (Baulcomb, 2011).

5.4.3.5.1. Observed impacts

Mortality risk in coastal areas is related to exposure and vulnerability of coastal populations to climate hazards (e.g., Myung and Jang, 2011). A regional analysis of changes in exposure, vulnerability, and risk indicates that although exposure to flood and cyclone hazards has increased since 1980, the risk of mortality has generally fallen. The reductions reflect a strengthening of the countries' capacity to respond to disasters (Box 5-1). However, mortality is still rising in the countries with the weakest risk governance capacities (UNISDR, 2011).

Coastal regions face a range of climate-sensitive diseases. Increased saline intrusion is linked to increased hypertension disease (Vineis et al., 2011), with greater occurrence in pregnant women living in coastal regions compared to further inland (Khan et al., 2008). Increasing temperature, humidity, and rainfall can increase vector-borne diseases such as malaria, dengue, leishmaniasis, and chikungunya (Pialoux et al., 2007; Stratten et al., 2008; Kolivras, 2010; van Kleef et al., 2010) and diarrhea, infectious gastrointestinal disease, rotovirus, and salmonella (e.g., Hashizume et al., 2007; Zhang et al., 2007, 2010; Chou et al., 2010; Onozuka et al., 2010). The parasitic disease schistosomiasis, endemic in many tropical and small island coastal regions (Section 29.3.3.2), is also sensitive to temperature increase (Mangal et al., 2008). Vibrio outbreaks (e.g., cholera) are sensitive to rainfall and SST (e.g., Koelle et al., 2005), and recent increased vibrio outbreaks in the Baltic have been linked to heat waves and low salinity (Baker-Austin et al., 2013). Harmful algal blooms (HABs) outbreaks (e.g., ciguatera) have been linked to SST variability (e.g., Erdner et al., 2008; Jaykus et al., 2008). However, in general there is *limited evidence* and *low confidence* in how global climate change will impact HABs (Section 6.4.2.3), suggesting the need for increased monitoring (Hallegraeff, 2010). Nontoxic blooms of high biomass can reduce biodiversity through oxygen depletion and shading (Erdner et al., 2008), with consequences for ecosystem and human nutrition and health.

5.4.3.5.2. Projected impacts

Under future climate conditions, expansion of brackish and saline water bodies in coastal areas under projected sea level rise may increase the incidence of vector-borne diseases (Ramasamy and Surendran, 2011), diarrhea, and hypertension (Vineis et al., 2011). Human responses to climate change may also influence outcomes on health; however, limited empirical climate-health data increases uncertainties on such projections (Kolstad and Johansson, 2011).

Evidence continues to emerge of the relation between climate and diseases that affect human health in the coastal zone including air and water temperature, rainfall, humidity, and coastal salinity. However, the

relations are often complex and vary between diseases and even regionally for the same disease. The interplay between climate and human systems with regard to health impacts is poorly understood and this continues to confound reliable projections of health impacts (*robust evidence*, *high agreement*).

5.4.4. Summary: Detection and Attribution

There is *high confidence* in the attribution to climate change of observed coastal impacts that are sensitive to ocean temperature change, such as coral bleaching and movements in species ranges. However, for many other coastal changes, the impacts of climate change are difficult to tease apart from human-related drivers (e.g., land use change, coastal development, pollution). Figure 5-5 shows changes of major phenomena observed in coastal systems and low-lying areas. Horizontal and vertical axes indicate the degree of confidence in detection of trends for phenomena, which are elements sensitive to climate change, and the degree of confidence in attribution of phenomena to climate change, respectively. Mainly phenomena with *high* to *very high confidence* in trend detection are illustrated in this figure.

The increase of coral bleaching and the shift in distribution and range limits of some species are attributed to climate change with *high confidence.* Mass coral bleaching coincided with positive temperature anomalies over the past 30 years. A poleward expansion of mangrove forests and some corals, and shifts of range limits of many intertidal species, are also attributed. Vegetated coastal habitats are declining globally. Coral cover and calcification have decreased in recent decades. Elevated temperatures along with ocean acidification reduce the calcification rate of corals. Although the attribution of decreased calcification to either climate- or human-related drivers is difficult, we have *medium confidence* that the primary climate-related driver is ocean warming globally. Seagrass meadows are already under stress due to climate change, particularly where maximum temperatures already approach their physiological limit. However, the decline of the distribution of mangroves and salt marshes is mainly linked with human activities, for example, deforestation and reclamation. Therefore the degree of their attribution to climate change is *very low*.

Globally beaches and shorelines have, in general, undergone net erosion over the past century or longer. There is *high confidence* in detection of increased beach erosion globally. However, attributing shoreline changes to climate change is still difficult owing to the multiple natural and human-related drivers contributing to coastal erosion (e.g., subsidence, decreased sediment delivery, land use change). There is *high confidence* that human pressures, for example, increased usage of surface water and groundwater resources for agriculture and coastal settlements, and river channel deepening, have led to increased saltwater intrusion and *low confidence* in attribution of saltwater intrusion to climate change.

The population living in coastal lowlands is increasing and more than 270 million people in 2010 are already exposed to flooding by the 1-in-100-year coastal flood (Mimura, 2013). Population growth and land subsidence in coastal lowlands are the major causes; therefore, there is *very low* attribution to climate change.

5.5. Adaptation and Managing Risks

5.5.1. Introduction

Coastal adaptation and risk management refer to a wide range of human activities related to the social and institutional processes of framing the

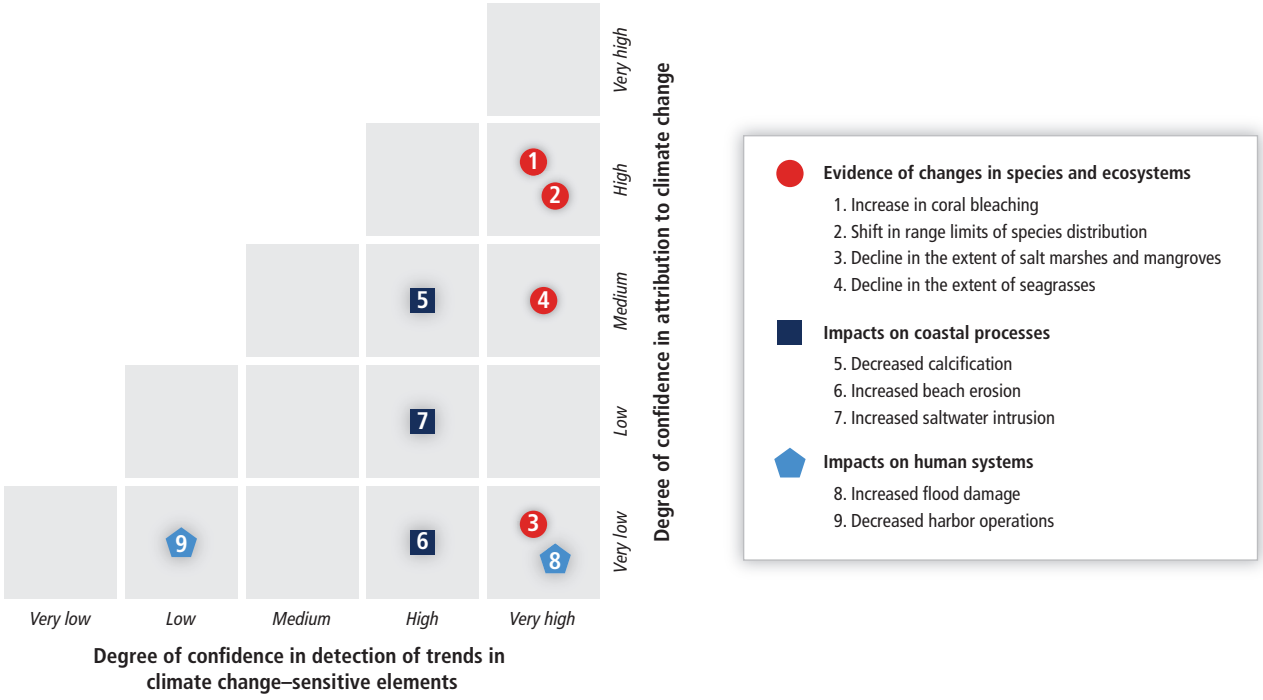

Figure 5-5 | Summary of detection and attribution in coastal areas.

Frequently Asked Questions

FAQ 5.3 | How can coastal communities plan for and adapt to the impacts of climate change, in particular sea level rise?

Planning by coastal communities that considers the impacts of climate change reduces the risk of harm from those impacts. In particular, proactive planning reduces the need for reactive response to the damage caused by extreme events. Handling things after the fact can be more expensive and less effective.

An increasing focus of coastal use planning is on precautionary measures, that is, measures taken even if the cause and effect of climate change is not established scientifically. These measures can include things like enhancing coastal vegetation and protecting coral reefs. For many regions, an important focus of coastal use planning is to use the coast as a natural system to buffer coastal communities from inundation, working with nature rather than against it, as in the Netherlands.

While the details and implementation of such planning take place at local and regional levels, coastal land management is normally supported by legislation at the national level. For many developing countries, planning at the grass roots level does not exist or is not yet feasible.

The approaches available to help coastal communities adapt to the impacts of climate change fall into three general categories:

1. Protection of people, property, and infrastructure is a typical first response. This includes "hard" measures such as building seawalls and other barriers, along with various measures to protect critical infrastructure. "Soft" protection measures are increasingly favored. These include enhancing coastal vegetation and other coastal management programs to reduce erosion and enhance the coast as a barrier to storm surges.
2. Accommodation is a more adaptive approach involving changes to human activities and infrastructure. These include retrofitting buildings to make them more resistant to the consequences of sea level rise, raising low-lying bridges, or increasing physical shelter capacity to handle needs caused by severe weather. Soft accommodation measures include adjustments to land use planning and insurance programs.
3. Managed retreat involves moving away from the coast and may be the only viable option when nothing else is possible.

Some combination of these three approaches may be appropriate, depending on the physical realities and societal values of a particular coastal community. The choices need to be reviewed and adjusted as circumstances change over time.

adaptation problem, identifying and appraising adaptation options, implementing options, and monitoring and evaluating outcomes (Chapters 2, 14, 15, 16, and 17). The governance of this process is challenging due to the complex, nonlinear dynamics of the coastal socio-ecological systems (Rosenzweig et al., 2011) as well as the presence of multiple management goals, competing preferences of stakeholders, and social conflicts involved (Hopkins et al., 2012). In many instances, coastal adaptation may thus be characterized to be a "wicked problem" (Rittel and Webber, 1973), in the sense that there is often no clear agreement about what exactly the adaptation problem is and there is uncertainty and ambiguity as to how improvements might be made (Moser et al., 2012).

Since AR4, the set of adaptation measures considered has been expanded specifically toward ecosystem-based measures (Section 5.5.2); novel approaches for appraising coastal adaptation decisions have been applied (Section 5.5.3.1) and the analysis of adaptation governance and the institutional context in which decisions are taken has progressed (Section 5.5.3.2). Progress has also been made in better integrating adaptation practices within existing policy frameworks (Section 5.5.4.1) as well as in implementing adaptation and identifying good practices (Section 5.5.4.2). A number of studies have also explored the global costs and benefits of coastal adaptation (Section 5.5.5); opportunities, constraints, and limits of coastal adaptation (Section 5.5.6); linkages between coastal adaptation and mitigation (Section 5.5.7); and the long-term commitment to coastal adaptation (Section 5.5.8).

5.5.2. Adaptation Measures

A detailed discussion on general adaptation needs and measures can be found in Chapter 14. As a first approximation, adaptation measures were classified into institutional and social measures (Section 14.3.2.1), technological and engineered measures (Section 14.3.2.2), and ecosystem-based adaptation measures (Section 14.3.2.3). In terms of coastal adaptation, most of the existing measures can be included within this classification.

The IPCC classification of coastal adaptation strategies consisting of retreat, accommodation, and protection (Nicholls et al., 2007) is now widely used and applied in both developed and developing countries (Boateng, 2010; Linham and Nicholls, 2012). This trilogy of strategies has expanded into broad approaches of retreat, defend, and attack (Peel, 2010). Protection aims at advancing or holding existing defense lines by means of different options such as land claim; beach and dune nourishment; the construction of artificial dunes and hard structures such as seawalls, sea dikes, and storm surge barriers; or removing invasive and restoring native species. Accommodation is achieved by increasing flexibility, flood proofing, flood-resistant agriculture, flood hazard mapping, the implementation of flood warning systems, or replacing armored with living shorelines. Retreat options include allowing wetlands to migrate inland, shoreline setbacks, and managed realignment by, for example, breaching coastal defenses allowing the creation of an intertidal habitat. The appropriate measure may depend on several factors requiring a careful decision-making and governance process (Section 5.5.3).

Since AR4, coastal adaptation options have been revised and summarized in several guidebooks (EPA, 2009; USAID, 2009; UNEP, 2010) including best practice examples. Especially relevant has been the growth of Community Based Adaptation (CBA) measures (*robust evidence*, *high agreement*). Table 5-4 compiles different examples of CBA measures in countries such as Bangladesh, India, and the Philippines.

Ecosystem-based adaptation is increasingly attracting attention (Munroe et al., 2011). Adaptation measures based on the protection and restoration of relevant coastal natural systems such as mangroves (Schmitt et al., 2013), oyster reefs (Beck et al., 2011), and salt marshes (Barbier et al., 2011) are seen as no- or low-regret options irrespective of future climate (Cheong et al., 2013; *medium evidence*, *high agreement*). Further work is still needed in order to make reliable quantitative estimates and predictions of the capability of some of these ecosystems to reduce wave, storm surge, and sea level rise impacts and in order to provide reliable cost-benefit analysis of how they compare to other measures based on traditional engineering approaches.

5.5.3. Adaptation Decision Making and Governance

Since AR4, progress has been made in understanding coastal adaptation decisions and governance. For a general treatment of adaptation decision making and governance, see Chapters 2, 15, and 17.

5.5.3.1. Decision Analysis

One specific quality of many coastal adaptation decisions is that these involve options with long (i.e., 30 and more years) investment time scales (e.g., land use planning, flood defenses, construction of housing, and transportation infrastructure; Section 5.5.2). For such decisions, standard methods that rely on probability distribution of outcomes, such as cost-benefit analysis under uncertainty, cannot be applied because of the difficulties, both in theory and practice, to associate probabilities to future levels of GHG emissions, which determine the level of impacts and outcomes (Lempert and Schlesinger, 2001; Hallegate, 2009; see also Section 17.3.6.2).

Alternative approaches that represent uncertainty not through a single probability distribution but through a range of scenarios have thus been applied to long-term coastal adaptation. Robust decision making (RDM), for example, refers to approaches where options that work well over a wide range of these scenarios are preferred (Lempert and Schlesinger, 2000; Lempert and Collins, 2007). RDM in this sense has been applied to, e.g., the Port of Los Angeles infrastructure (Lempert et al., 2012).

Another set of approaches uses the criterion of flexibility to decide between alternative strategies. Flexible and reversible options are favored over non-flexible and non-reversible ones and decisions are delayed to keep future options open (Hallegate, 2009). The adaptation pathways approach, for example, implements the criterion of flexibility by characterizing alternative strategies in terms of two attributes: (1) adaptation tipping points (ATPs), which are points beyond which strategies are no longer effective (Kwadijk et al., 2010); and (2) what alternative strategies are available once a tipping point has been reached (Haasnoot et al., 2013). Importantly, the exact time when an ATP is reached does not matter; it is rather the flexibility of having alternative strategies available that is driving the decision. Prominent applications of this approach include the Thames Estuary 2100 Plan (Penning-Roswell et al., 2012; Box 5-1), the Dutch Delta Programme (Kabat et al., 2009), and the New York City Panel on Climate Change (Rosenzweig et al., 2011).

5.5.3.2. Institution and Governance Analysis

Decisions are made within a context. Institution and governance analysis comprise a variety of approaches that aim at describing this context as well as at explaining the emergence and performance of institutions and governance structures (GS). Institution analysis is particularly relevant to coastal adaptation, because deciding between options and implementing them is an ongoing process involving complex inter-linkages between public and private decisions at multiple levels of decision making and in the context of other issues, existing policies, conflicting interests, and diverse GS (e.g, Few et al., 2007; Urwin and Jordan, 2008; Hinkel et al., 2010; see also Sections 2.2.2, 2.2.3). The non-consideration of this context may hinder or mislead adaptation decisions and implementations as reported by the emerging literature on barriers to adaptation (Section 5.5.5). Institution analysis strives to understand how this context shapes decisions, and insights gained may be employed to craft effective institutions and policies for adaptation.

For coastal adaptation, the effectiveness of existing GS is often hindered owing to a lack of horizontal (i.e., within the same level of decision making) and vertical (i.e., between different levels of decision making) integration of organizations and policies (*high confidence*). Storbjörk and Hedren (2011), for example, report on a weak vertical administrative interplay in coastal GS in Sweden. In the UK, the effectiveness of local GS of Coastal Partnership is found to be limited because these are poorly integrated with higher level policies (Stojanovic and Barker, 2008). In the UK, national level coastal recommendations are difficult to translate into local level actions (Few et al., 2007) and, in the USA, coastal policies often have ambiguous or contradictory goals (Bagstad et al., 2007). In a number of African cases, coastal policies are found not to take into account longer term climate change (Bunce et al., 2010).

Box 5-1 | London's Thames Estuary 2100 Plan: Adaptive Management for the Long Term

The Environment Agency in Britain has recently developed the Thames Estuary 2100 plan (TE2100) to manage future flood threat to London (Environment Agency, 2012). The motivation was a fear that due to accelerated climate change-induced sea level rise the time could already be too short for replacing the Thames Barrier (completed in 1982) and other measures that protect London, because such major engineering schemes take 25 to 30 years to plan and implement. An adaptive plan that manages risk in an iterative way was adopted based on the adaptation pathway approach (Penning-Rowsell et al., 2012; see also Section 5.5.3.1; Figure 5-6). This plan includes maintaining the existing system in the first 25 years, then enhancing the existing defenses in a carefully planned way over the next 25 to 60 years, including selectively raising defenses and possibly over-rotating the Barrier to raise protection standards. Finally, in the longer term (beyond 2070) there will be the need to plan for more substantial measures if sea level rise accelerates. This might include a new barrier, with even higher protection standards, probably nearer to the sea, or even a coastal barrage. In the meantime the adaptive approach requires careful monitoring of the drivers of risk in the Estuary to ensure that flood management authorities are not taken by surprise and forced into emergency measures.

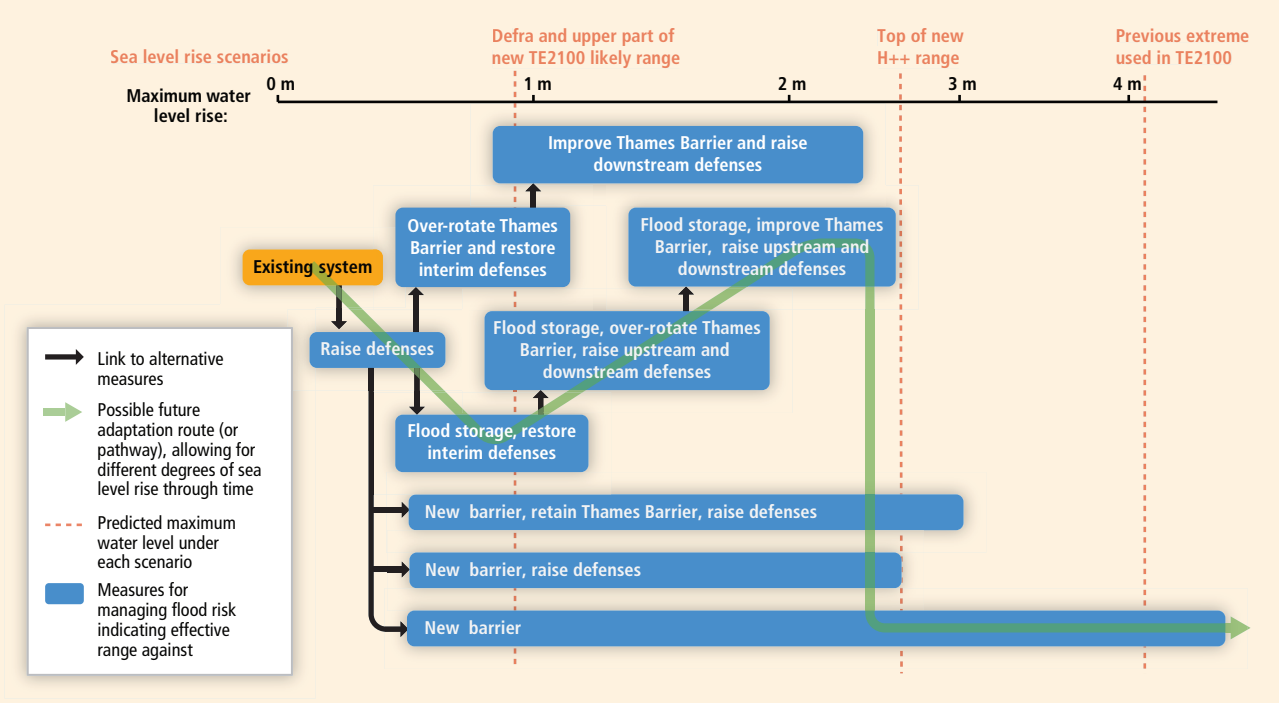

Figure 5-6 | Adaptation measures and pathways considered in the TE2100 project. The boxes show the measures and the range of sea level rise over which the measures are effective. The black arrows link to alternative measures that may be applied once a measure is no longer effective. The red lines show various 21st century sea level rise scenarios used in the analysis including a conservative estimate of about 0.9 m by the UK Department for Environment Food and Rural Affairs ('Defra and upper part of new TE2100 likely range'), a high-level scenario ('Top of new H++ range'), and an extreme scenario of over 4 meters ('previous extreme used in TE2100'). The fat green line shows a possible future adaptation route (or pathway), allowing for different degrees of sea level rise through time (adapted from Lowe et al., 2009).

Governance issues are particularly challenging when considering planned retreat (*medium evidence*). While managed realignment is on the political agenda in Germany and the UK, the political costs of doing so are high, as both the existing GS as well as public opinion are geared toward protection (e.g., Tunstall and Tapsell, 2007), so that short election cycles do not provide incentives for politicians to undertake actions that may produce benefits in the long term (Few et al., 2007; Rupp-Armstrong and Nicholls, 2007). Along the Queensland coast in Australia the option of planned retreat is disappearing because of rapid coastal development and liability laws favoring development. To prevent this, risks and responsibilities would need to be redistributed from the governments to the beneficiaries of this development (Abel et al., 2011).

While institutional factors are decisive in enabling coastal adaptation (*high confidence*), the role of institutions in coastal adaptation is generally under-researched. The majority of studies are descriptive. Institutional analysis striving to understand which GS emerge and are effective depending on both biophysical and social system characteristics as

found in the fields of socio-ecological systems (Dietz et al., 2003; Folke et al., 2005; Ostrom 2007, 2009) and institutional economics (Hagedorn et al., 2002; Bougherara et al., 2009) are practically nonexistent.

5.5.4. Implementation and Practice

Since AR4, more experience has been gained in coastal adaptation implementation and practice. Generally, adaptation is not carried out stand-alone but in the context of already existing policy and practice frameworks. Section 5.5.4.1 assesses frameworks that are particularly relevant for coastal adaptation, and Section 5.5.4.2 assesses the experience as well as principles and compiled best practice guidelines.

5.5.4.1. Frameworks

The issues for coastal adaptation are not radically different from issues encountered within ICZM, which offers an enabling environment for adaptation practice (Celliers et al., 2013). ICZM is a long-term, institutionalized and iterative process that promotes the integration of coastal activities, relevant policymakers, practitioners, and scientists across coastal sectors, space and organizations with a view to use coastal resources in a sustainable way (Christie et al., 2005; Kay and Alder, 2005; Sales, 2009; WGII AR5 Glossary). Considering climate change in this framework does not mean radical changes to ICZM, because ICZM already emphasizes the integration of coastal issues across sectors and policy domains as well as the long-term perspective (e.g., Hofstede, 2008; Falaleeva et al., 2011). The major difference of coastal adaptation from ICZM is coping with greater uncertainty, longer time frames in planning (beyond 30 years), and long-term commitments inherent to climate change (Tobey et al. 2010). So far, however, there is *limited evidence* and *low agreement* on the effectiveness of ICZM alone or combined with climate change adaptation. Even though ICZM has been applied throughout the world for over 40 years, many obstacles to its successful implementation still remain (*high confidence*). Generally, there is a lack of empirical research evaluating ICZM (Stojanovic et al., 2004; Stojanovic and Ballinger, 2009). A recent review of ICZM in Europe concluded that the complexity of coastal regulations, demographic deficits, lack of sustainable finance and a failure to involve communities, business, and industry hinder its implementation (Shipman and Stojanovic, 2007). Developing countries in particular struggle to meet the goals of ICZM owing to a lack of qualified human resources, a lack of human, legal, and institutional capacities (Isager, 2008; González-Riancho et al., 2009), difficulties in integrating policy across multiple coastal agencies (Martinez et al., 2011; Ibrahim and Shaw, 2012), power (abuse) of the majority political party or political leaders (Isager, 2008; Tabet and Fanning, 2012), the lack of long-term financial commitment of donors (González-Riancho et al., 2009; Ibrahim and Shaw, 2012), and a lack of knowledge regarding the coastal system (González-Riancho et al., 2009).

Another prominent framework used for coastal adaptation practice is adaptive management (AM), which has been developed as a response to the deep uncertainty characterizing ecosystem management, where it is often impossible to predict outcomes of management interventions. AM thus aims to test management hypothesis by implementing them, monitoring their outcomes and learning from these to refine the management hypothesis to be applied (Holling, 1978; Walters, 1986). There are numerous applications of AM to coastal management (e.g., Walters, 1997; Marchand et al., 2011; Mulder et al., 2011), but there is *limited evidence* of its long-term effectiveness. Limitations of AM are also notable, such as the potential high cost of experimentation and a range of institutional barriers hindering the delivery of flexible management approaches (e.g., McLain and Lee, 1996).

Community-based adaptation (CBA) refers to the generation and implementation of locally driven adaptation strategies that address both climate change impacts and development deficits for the climate-vulnerable poor and that aim to strengthen the adaptive capacity of local people to climate and non-climate risk factors (Nicholls et al., 2007; Reid et al., 2009; Ayers and Dodman, 2010; Ayers and Huq, 2013; see also Sections 14.2.1, 15.4.3.1, 24.4.6.5). CBA is a bottom-up approach to adaptation involving all relevant stakeholders, especially local communities (Ayers and Huq, 2009; UNDP, 2010; Riadh et al., 2012) (Table 5-4). As such, CBA approaches have been developed through active participatory processes with local stakeholders (Ayers and Forsyth, 2009), and operated on a learning-by-doing, bottom-up, empowerment paradigm (Kates, 2000; Huq and Reid, 2007).

CBA experiences emphasize that it is important to understand a community's unique perception of its adaptive capacities in order to identify useful solutions (Parvin et al., 2008; Badjeck et al., 2010; Paul and Routray, 2010) and that scientific and technical information on anticipated coastal climate impacts needs to be translated into a suitable language and format that allows people to be able to participate in adaptation planning (Saroar and Routray, 2010). Furthermore, effective CBA needs to consider measures that cut across sectors and technological, social, and institutional processes, as technology by itself is only one component of successful adaptation (Pelling, 2011; Rawlani and Sovacool, 2011; Sovacool et al., 2011).

Efforts are also being made to integrate climate change adaptation into Disaster Risk Reduction (DRR) frameworks (Mercer, 2010; Polack, 2010; Romieu et al., 2010; Gero et al., 2011) and adaptation practice is likely to move forward as climate change adaptation (CCA) converges with disaster risk reduction (UNISDR, 2009; Setiadi et al., 2010; Tran and Nitivattananon, 2011; Hay, 2012). In Japan, for example, coastal climate change adaptation has been mainstreamed into the framework of Coastal Disaster Management in the aftermath of the 2011 Tohoku Earthquake Tsunami. The priority of upgrading coastal defenses in the face of sea level rise is thereby judged from the potential damage on the assets in predicted inundation areas on the one hand as well as from the age and earthquake resistance of the coastal structures on the other hand (Central Disaster Management Council, 2011; Committee on Adaptation Strategy for Global Warming in the Coastal Zone, 2011). Other important policy and practice frameworks in place in the coastal zone include poverty reduction and development (Mitchell et al., 2010).

5.5.4.2. Principles, Guidance, and Experiences

Much of the observed adaptation practice deals with the coastal hazards of erosion and flooding (Hanak and Moreno, 2012). In many

Table 5-4 | Community-based adaptation measures.

Impact	Type of option	Measures	Brief description	References
Increased salinity	New and diversified livelihoods	Saline-tolerant crop cultivation	Farmer production of saline-tolerant multi-vegetable varieties and non-rice crops	Ahmed (2010); Rabbani et al. (2013)
	New and diversified livelihoods	Keora nursery	Mangrove fruit production to develop local female entrepreneurship	Ahmed (2010)
	New and diversified livelihoods	Crab fattening	Collection, rearing, and feeding of crabs for 15 days to increase local market value	Pouliotte et al. (2009)
	Structural	Homestead protection	Houses constructed on raised foundations to mitigate salinity ingress	Ayers and Forsyth (2009)
Flooding/ inundation	Socio-technical	Disaster management committees	Multi-community stakeholder committees established to discuss disaster preparedness and response on a monthly basis	Ahammad (2011)
	Socio-technical	Early flood warning systems	Established systems converted into a language and format understood by local communities; warning dissemination through community radio services	Ahmed (2005); Saroar and Routray (2010)
	New and diversified livelihoods	Aquaculture: cage and integrated approaches	Small-scale fish culture in cages on submerged agriculture land; aquaculture integrated with other livelihood practices	Pomeroy et al. (2006); Pouliotte et al. (2009); Khan et al. (2012)
	New and diversified livelihoods	Embankment cropping	Growing different vegetable varieties around heightened shrimp enclosures/coastal polders for productive use of fallow land	Ahmed (2010)
	New and diversified livelihoods	Hydroponics	Cultivating vegetables and other crops on floating gardens	Ayers and Forsyth (2009); Ahmed (2010); Dev (2013)
Cyclones/ storm surges	Structural/hard	Homestead reinforcement	Low-cost retrofitting to strengthen existing household structures, especially roofs; strict implementation of building codes	Sales (2009); Ahmed (2010)
	Structural/soft	Homestead ecosystem protection	Plantation of specific fruit trees around homestead area	Haq et al. (2012)
	Structural/hard	Underground bunker construction	Underground bunker established, providing protected storage space for valuable community assets	Raihan et al. (2010)
Sea level rise	Institutional	Risk insurance mechanisms	Farmers educated on comprehensive risk insurance, focusing on sea level rise and coastal agriculture	Khan et al. (2012)
Multi-coastal impacts	Institutional	Integrating climate change into education	Formal and informal teacher training and curriculum development on climate change, vulnerability, and risk management	Ahmed (2010)
	Institutional	Integrated coastal zone management (ICZM) plan	ICZM plan development at local institutional level, including land and sea use zoning for ecosystem conservation	Sales (2009)
	Structural/soft	Restoration, regeneration and management of coastal habitats	Community-led reforestation and afforestation of mangrove plantations, including integration of aquaculture and farming to increase household income levels	Rawlani and Sovacool, (2011); Sovacool et al. (2012)
	Institutional	Community participation in local government decision-making	Active female participation in local government planning and budgeting processes to facilitate delivery of priority coastal adaptation needs	Faulkner and Ali (2012)
	Institutional/ socio-technical	Improved research and knowledge management	Establishment of research centers; community-based monitoring of changes in coastal areas	Sales (2009); Rawlani and Sovacool (2011)

parts of the world, small island indigenous communities address climate change consequences based on their own traditional knowledge (Percival, 2008; Langton et al., 2012; Nakashima et al., 2012). Long-term adaptation to sea level rise has been confined to a few major projects such as the Venice Lagoon project, the Thames Estuary 2100 project (Box 5-1), and the Delta Programme, Netherlands (Norman, 2009).

Through the Delta Programme, the Dutch government has set out far-reaching recommendations on how to keep the country flood-proof over the 21st century taking into account a sea level rise as high as 0.65 to 1.3 m by 2100. These recommendations constitute a paradigm shift from "fighting" the forces of nature with engineered structures to "working with nature" and providing "room for river" instead (Kabat et al., 2009). The recommendations include soft and environmentally friendly solutions such as preserving land from development to accommodate increased river inundation, maintaining coastal protection by beach nourishment, improving the standards of flood protection, and putting in place the necessary political-administrative, legal, and financial resources (Stive et al., 2011).

From adaptation experiences, good practices (practices that have shown consistently better results and could be used as benchmark) have been derived. For some European cases, for example, McInnes (2006) has collected good practices for coastlines facing coastal erosion, flooding, and landslide events. In the California adaptation study that includes coasts, the lessons learnt include using best available science, decision on goals and early actions, locating relevant partners, identification and elimination of regulatory barriers, and encouragement of introduction of new state mandates and guidelines (Bedsworth and Hanak, 2010). Boateng (2010) presented 15 case studies from 12 countries of best practice in coastal adaptation to help coastal managers and policymakers. Bangladesh provides good examples on awareness raising, disaster warning and control, and protective building measures (Martinez et al., 2011). In general, documentation on good adaptation practices for coasts is improving.

In addition, numerous principles have been set forward. In a broad-scale assessment of climate change threats to Australia's coastal ecosystems, seven principles in adaptation were suggested: clearly defined goals by location, thorough understanding of connectivity within and between

ecosystems, consideration of non-climatic drivers, involvement of all relevant stakeholders, easily available and shared data, re-thinking of existing policy and planning constraints, and adaptation at local/regional scales (Hadwen et al., 2011). Based on Oxfam's adaptation programs in South Asia that include coastal communities, additional principles presented include a focus on the poor, vulnerable, and marginalized; community or local ownership; flexible and responsive implementation; and preparation for future and capacity building at multiple levels (Sterrett, 2011). An assessment of worldwide case studies indicates the importance of knowledge transfer of good practice methods for scaling up adaptation strategies in and between regions and beyond the national scale (Martinez et al., 2011).

Further principles reported include: Information on efficient adaptation options alone (as assessed through DA approaches) may not fully serve the needs of managers and must to be supplemented by financial and technical assistance as well as boundary organizations that serve as an interface between science and practice (Tribbia and Moser, 2008). The adaptation and decision-making processes should be participatory and inclusive, integrating all relevant stakeholders in a way that is culturally appropriate (Milligan et al., 2009; Nunn, 2009). The adaptation processes should foster mutual learning, experimentation, and deliberation among stakeholders and researchers (Fazey et al., 2010; Kenter et al., 2011). For example, neither scientific climate knowledge alone nor indigenous knowledge alone is considered sufficient for coastal adaptation (Sales, 2009; Dodman and Mitlin, 2011; Bormann et al., 2012). Finally, since coastal systems are complex, diverse, and dynamic, their governance requires experimentation and learning by doing (Jentoft, 2007).

In summary, a wealth of adaptation activities can now be observed in the coastal zone that depend on technology, policy, financial, and institutional support, and are supported by documentation on good practices (*very high confidence*). ICZM, with its emphasis on integration, is likely to remain a major framework for coastal adaptation. While there is *high agreement* on adaptation principles, there is to date little systematic review of and hence *limited evidence* on why a given principle or approach is effective in a given context (and not in another), which emphasizes the need for research to better understand this context (Section 5.5.3.2). Some of the literature on adaptation practice needs to be treated with caution, because normative principles that have been established *ex ante* are not systematically distinguished from *ex post* evaluations of the experiences carried out. Despite the wealth of coastal adaptation activities, it must, however, be emphasized that meeting the multiple goals of coastal adaptation, improving governance, accounting for the most vulnerable populations and sectors and fully integrating consideration of natural ecosystems is still largely aspirational. Meanwhile, development continues in high-risk coastal areas, coastal ecosystems continue to degrade in many regions, coastal freshwater resources are being overexploited in many highly populated areas, and vulnerability to coastal disasters grows (e.g., Shipman and Stojanovic, 2007; McFadden, 2008; Jentoft, 2009; Mercer, 2010).

5.5.5. Global Adaptation Costs and Benefits

This section reports on studies that provide internally consistent estimates of the direct costs of sea level rise impacts and adaptation at global scales. These studies have used the models FUND and DIVA, which are described in Section 5.4.1. Studies that use computable general equilibrium models and growth models to estimate the indirect and dynamic costs of climate change, including sea level rise, are reviewed in Chapter 10.

Generally, cost estimates are difficult to compare across studies owing to differences in scenarios used, impacts and adaptation options considered, methodologies applied, and baseline conditions assumed. Global adaptation costs have only been assessed for protection via dikes and nourishment. Nicholls et al. (2011) estimate annual adaptation cost in terms of dike construction, dike maintenance, and nourishment to be US$25 to 270 billion per year in 2100 under a 0.5 to 2.0 m GMSLR for 2005–2100. Anthoff et al. (2010) estimate the net present value of dike construction costs for 2005–2100 to be US$80 to 120 billion for 0.5 m GMSLR and US$900 to 1100 billion for a 2 m GMSLR, respectively.

The available global studies show that it is economically rational to protect large parts of the world's coastline during the 21st century against sea level rise impacts of increased coastal flood damage and land loss (Nicholls and Tol, 2006; Anthoff et al., 2010; Hinkel et al., 2013; *limited evidence*, *high agreement*). For dry land and wetlands loss, the FUND model shows that cost-benefit analysis would justify protecting 80% of the exposed coast in all but 15 countries under a GMSLR of 20 to 40 cm per century (Nicholls and Tol, 2006). Using the same method, Nicholls et al. (2008) show that under extreme GMSLR of up to 4 m in 2100, this fraction would drop to 30% to 50%. For coastal flooding, an application of DIVA shows that, for 21st century GMSLR scenarios of 60 to 126 cm, the global costs of protection through dikes (levees) are much lower than the costs of damages avoided through adaptation (Hinkel et al., 2013).

At the same time, costs and benefits of sea level rise impacts and adaptation vary strongly between regions and countries with some developing countries and small islands reaching limits of adaption or not being able to bear the costs of impacts and adaptation (*limited evidence*, *high agreement*) (Section 29.6.2.1). The cost of 1 m of GMSLR in 2100 (considering land loss due to submergence and protection costs) is projected to be above 1% of national GDP for Micronesia, Palau, the Bahamas, and Mozambique (Anthoff et al., 2010). For coastal flooding, annual damage and protection costs are projected to amount to several percentages of the national GDP for small island states such as Kiribati, the Solomon Islands, Vanuatu, and Tuvalu under GMSLR projections of 0.6 to 1.3 m by 2100 (Hinkel et al., 2013). Further substantial costs arise, particularly for developing countries owing to their current adaptation deficit (i.e., coastal defenses are not adapted to the current climate variability), which is not well understood and requires further analysis (Parry et al., 2009). For example, the adaption deficit of Africa with regard to coastal flooding is estimated at US$300 billion (Hinkel et al., 2011) and that of Bangladesh with respect to cyclones at US$25 billion (World Bank, 2011).

Several methodological gaps remain. As there are so few studies on the costs and benefits of sea level rise at a global level, uncertainties are largely unknown and the need for further research is great. The socioeconomic drivers, sea level rise scenarios, and impacts considered as well as damages and losses valued are incomplete. For example, costs of salinity

intrusion, land loss due to increased coastal erosion, cost of forced migration due to permanent inundation, the backwater effect, and the impact of sea level rise in combination with other drivers on ecosystems have not been assessed at global scales (Section 5.5.5). Generally for sea level rise impacts, it is difficult to establish a "no adaptation" baseline and the choice of the baseline changes damage costs (Yohe et al., 2011).

Another gap is related to the fact that global studies have focused on protection via hard structures while many more potentially cheaper or socially preferable measures are available including "soft" protection, retreat, and accommodation measures (Section 5.1). Future work needs to consider trade-offs between all available measures. Hard protection measures, for example, may incur additional costs on adjacent unprotected coasts (Brown et al., 2013) or destroy coastal wetlands through coastal squeeze (Section 5.4.2.3). While the costs of "soft" protection measures such as ecosystem-based adaptation (EBA) are largely unknown (Linham and Nicholls, 2010; Engineers Australia, 2012), these may provide additional benefits in the form of a variety of ecosystem services (Alongi, 2008; IUCN, 2008; Anthony et al., 2009; Vignola et al., 2009; Pérez et al., 2010; Espinosa-Romero et al., 2011; McGinnis and McGinnis, 2011; Zeitlin et al., 2012). Finally, it must be noted that protection also further attracts people and development to the floodplain, which in turn increases the risk of potential catastrophic consequence in the case of defense failure. This is particularly true for many coastal cities such as London, Tokyo, Shanghai, Hamburg, and Rotterdam that already rely heavily on coastal defenses (Nicholls et al., 2007).

5.5.6. Adaptation Opportunities, Constraints, and Limits

There is a growing recognition of the potential co-benefits and new opportunities that can be achieved by mainstreaming adaptation with existing local to national goals and priorities (Section 14.3.4). DRR and adaptation share the common goals of reducing vulnerability against impacts of extreme events while creating strategies that limit risk from hazards (IPCC, 2012). This is especially true in coastal areas where extreme flooding events due to severe storm surges are one of the main sources of hazard. Besides, integrating adaptation with national and local planning can also contribute to building resilience in coastal areas.

EBA is considered to be an emerging adaptation opportunity (Munroe et al. 2011) (Section 16.6, Box CC-EA). In coastal areas, the conservation or restoration of habitats (e.g., mangroves, wetlands, and deltas) can provide effective measures against storm surge, saline intrusion, and coastal erosion by using their physical characteristics, biodiversity, and the ecosystem services they provide as a means for adaptation (Borsje et al., 2011; Jones et al., 2012; Cheong et al., 2013; Duarte et al., 2013b; see also Section 5.5.7).

Since AR4, a variety of studies have been published providing a better understanding of the nature of the constraints and limits to adaptation, both generally (Sections 16.3, 16.4) and more specifically in the coastal sector (e.g., Ledoux et al., 2005; Moser et al., 2008; Tribbia and Moser, 2008; Bedsworth and Hanak, 2010; Frazier et al., 2010; Saroar and Routray, 2010; Mozumber et al., 2011; Storbjörk and Hedrén, 2011; Lata and Nunn, 2012).

Constraints specific to coastal adaptation are polarized views in the community regarding the risk of sea level rise and concerns regarding the fairness of retreat schemes in Australia (Ryan et al., 2011); lack of awareness of sea level rise risks and spiritual beliefs in Fiji (Lata and Nunn, 2012); insufficient budget for the development of adaptation policies and other currently pressing issues in the USA (Tribbia and Moser, 2008; Mozumber et al., 2011); distinct preferences for retreat options depending on several social and exposure conditions in Bangladesh (Saroar and Routray, 2010); and the need to provide compensatory habitats under the Habitats Regulations and lack of local public support in the UK (Ledoux et al., 2005). Other relevant constraints include the lack of locally relevant information, resource tenure, and political will, especially critical in developing countries (*robust evidence*, *high agreement*). Besides, a gap exists between the useful climate information provided by scientists and the one demanded by decision makers.

Different constraints typically do not act in isolation, but in interacting bundles (*robust evidence*, *high agreement*). Therefore it is difficult to predict which constraints matter most in any specific context but instead multiple constraints need to be addressed if adaptation is to move successfully through the different stages of the management process (Moser and Ekstrom, 2010; Londsdale et al., 2010; Storbjörk, 2010; *medium evidence*, *high agreement*). Besides, some factors can act as enablers and add to the adaptation capacity, while acting as constraints for others (Burch, 2010; Storbjörk, 2010; *medium evidence*, *high agreement*).

Finally, a common concern emerging from the literature reviews (Biesbroek et al., 2010; Ekstrom et al., 2011) is that some critical constraints arise from the interactions across policy domains, existing laws and regulations, and long-term impacts of past decisions and policies (*low evidence*, *high agreement*).

A limit is reached when adaptation efforts are unable to provide an acceptable level of security from risks to existing objectives and values and prevent the loss of key attributes, components, or services of an ecosystem (Box 16-1; Sections 16.2, 16.5) and may arise as a result of most of the constraints described above.

Regarding coastal areas, it is widely recognized that biophysical limitations arise, for example, in small island developing states where adaptation through retreat to increasing impact of sea level rise in conjunction with storm surges and flooding is not an option due to limited high land availability, creating a temporary and eventually permanent human displacement from low-lying areas (Pelling and Uitto, 2001; *medium evidence*, *high agreement*). Nicholls et al. (2011) show that only a limited number of adaptation options are available for specific coastal areas if sea level exceeds a certain threshold (1 m) at the end of the century.

Regarding natural (unassisted) adaptation, several researchers have examined biophysical limits, for example, of coastal marshes (Craft et al., 2009; Langley et al., 2009; Mudd et al., 2009; Kirwan et al., 2010), and found that under certain nonlinear feedbacks among inundation, plant growth, organic matter accretion, and sediment deposition coastal wetlands can adapt to conservative rates of sea level rise (SRES A1B) if suspended sediment surpasses a certain threshold. In contrast, even coastal marshes with high sediment supplies will submerge near the

end of the 21st century under scenarios of more rapid sea level rise (e.g., those that include ice sheet melting).

Increased ocean acidification is expected to limit adaptation of coral reefs to climate change (Boxes CC-OA and CC-CR).

5.5.7. Synergies and Trade-offs between Mitigation and Adaptation

Klein et al. (2007, p. 749) defined trade-offs between mitigation and adaptation as the "balancing of adaptation and mitigation when it is not possible to carry out both activities fully at the same time (e.g., due to financial or other constraints)." Successful adaptive coastal management of climate risks will involve assessing and minimizing potential trade-offs with other non-climate policy goals (e.g., economic development, enhancement of coastal tourism) and interactions between adaptation and mitigation (e.g., Brown et al., 2002; Tol, 2007; Barbier et al., 2008; Bunce et al., 2010).

Adaptation will be the predominant approach to reducing climate risks to coastal communities, populations, resources, and activities over the 21st century as large increases in sea level rise cannot be ruled out (WGI AR5 Section 13.5.2) and because of the time lag between emissions reductions, temperature changes, and impacts on global sea levels (Nicholls et al., 2007, 2011; see also Section 5.5.7). Still, positive synergies and complementarities between mitigation and adaptation in the coastal sector exist.

Since AR4, a series of studies have pointed out that marine vegetated habitats (seagrasses, salt marshes, macroalgae, or mangroves) contribute to almost 50% of the total organic carbon burial in ocean sediments leading to the so-called Blue Carbon (coastal carbon stocks) strategies (Nellemann et al., 2009; McLeod et al., 2011; Duarte et al., 2013b). These strategies aim at exploring and implementing the necessary mechanisms allowing Blue Carbon to become part of emission and mitigation protocols along with other carbon-binding ecosystems such as rainforests (Nellemann et al., 2009). Besides, marine vegetated habitats provide additional functions including the buffering of impacts against storm surges and waves, soil preservation, raising the seafloor, and shelter for fish nursery or habitat protection (Alongi, 2002; Kennedy and Björk, 2009; Duarte et al., 2013b). Consequently, restoration or ecosystem engineering of marine vegetated areas can be considered as a good example of positive synergies between adaptation and mitigation in coastal areas (Borsje et al., 2011; Jones et al., 2012; Duarte et al., 2013b) and should be further explored to be considered as a valid alternative in the portfolio of measures for climate change mitigation and adaptation. Only recently results have been presented on the role of a 1700 ha seagrass restoration in carbon storage in sediments of shallow coastal ecosystems in Virginia (USA). Restored seagrass meadows are expected to accumulate carbon at a rate comparable to ranges measured in natural seagrass meadows within 12 years of seeding, providing an estimated social cost of US$4.10 ha^{-1} yr^{-1} (Greiner et al., 2013).

Many coastal zone-based activities and various coastal management strategies involve emissions of GHGs. Reduction or cessation of some of them may have positive implications for both mitigation and adaptation. Limiting offshore oil production may imply a net reduction in GHG emissions depending on what form of energy replaces it, but also a reduced risk of oil spills, a reduction of stresses on the marine/coastal ecosystems, and variable socioeconomic impacts on human communities and public health (O'Rourke and Connolly, 2003). This may result in reduced vulnerability or increased resilience and consequently could prove positive for adaptation. However, this measure would increase the vulnerability of countries whose economies are highly dependent on oil extraction.

Some coastal adaptation options may have potentially negative implications on mitigation. Relocation of infrastructure and development out of the coastal floodplains (retreat) will imply increase in one-time GHG emissions due to rebuilding of structures and possible increase in low-density urban development and ongoing transportation-related emissions (Biesbroek et al., 2010). The building or upgrading of coastal protection structures or ports will also imply an increased energy use and GHG emissions related to construction (e.g., cement production) (Boden et al., 2011).

Similarly, actions beneficial for mitigation may result in potential negative impacts for adaptation. A more compact coastal urban design, increasing development in floodplains (Giridharan et al., 2007), or the development of marine renewable energy (Boehlert and Gill, 2010) may introduce additional drivers on coastal systems reducing coastal resilience and adaptive capacity.

5.5.8. Long-Term Commitment to Sea Level Rise and Adaptation

In AR4, both WGI and WGII highlighted the long-term commitment to sea level rise (Meehl et al., 2007; Nicholls et al., 2007), which means that sea levels will continue to rise for centuries due to global warming until reaching equilibrium conditions even if climate forcing is stabilized, because there is a delay in the response of sea level rise to global warming (WGI AR5 Section13.4.1). WGI AR5 has now assessed GMSLR until 2500 and this shows that even with aggressive mitigation measures (RCP2.6), sea level continues to rise after 2100 (Table 5-1; see also WGI AR5 Sections 13.5.1, 13.5.4). With more moderate (RCP4.5.) and little (RCP8.5) mitigation, larger ongoing increases in sea level are expected, lasting for several centuries. Note that the ranges given after 2100 are only model spread and not likely ranges. Looking beyond 2500, Levermann et al. (2013) project that GMSL will rise on average by about 2.3 m per degree Celsius of global warming within the next 2000 years. Under present levels of global warming, this means that we have already committed to a long-term sea level rise of 1.3 m above current levels (Strauss, 2013). For other climate-related drivers, responses to global warming levels are more immediate. For ocean acidification, for example, pH rise would cease several decades after strict CO_2 emission reductions begin (Bernie et al. 2010; see also Section 19.7.1).

This long-term commitment to sea level rise means that there is also a long-term commitment to sea level rise impacts and adaptation. Few studies have considered this and, from a methodological point of view, it is difficult to look at socioeconomic conditions and human responses on such large temporal scales. A limited number of studies have estimated

the effects of mitigation on coastal impacts on human settlements and adaptation for the 21st century (Section 5.4.3.1). These studies show that despite the delayed response of sea level rise to global warming, mitigation can reduce impacts significantly already during the 21st century. These studies also show that for most urban areas, coastal protection is cost-efficient in reducing impacts during the 21st century (Section 5.5.5). Past and current adaptation practice also confirms this: cities such as Tokyo and Shanghai have protected themselves against local sea level rise of several meters during the 20th century and the Dutch and UK governments have decided that they can protect urban Netherlands and London against 21st century sea level rise above 1 m (Section 5.5.4). Not protecting cities such as Amsterdam, Rotterdam, and London during the 21st century is not an option. On the other hand, there are coastal areas such as small islands where protecting against several meters of sea level rise in the long term is not a viable option. Failing to mitigate, thus increasingly commits us to a world where densely populated areas lock into a trajectory of increasingly costly hard defenses and rising residual risks on the one hand and less densely populated areas being abandoned on the other hand. Mitigation thus plays, in the long term, a very important role in avoiding climate change impacts in coastal areas by reducing the rate of sea level rise and providing more time for long-term strategic adaptation measures to be adopted. However, even if anthropogenic CO_2 emissions were reduced to zero, sea levels would continue to rise for centuries, making adaptation in coastal areas inevitable.

5.6. Information Gaps, Data Gaps, and Research Needs

This chapter has updated knowledge on the impacts of climate change on the coastal systems not in isolation but also from the perspective of overexploitation and degradation that have been responsible for most of the historical changes. There is a better understanding of the varying impacts of weather and climate extremes and long-term sea level rise on human systems.

That sea levels will rise is a confident projection of climate science but uncertainties around the magnitude of future sea level rise remain large. The rates and magnitude of sea level rise are summarized in Table 5-1 but, under present levels of global warming, we are already committed to 1.3 m future sea level rise above current levels (Section 5.5.8). However, many sea level rise assessments are not provided at spatial or temporal scales most relevant for decision makers who require information on baseline conditions and projections of change (Kettle, 2012) of RSLR (i.e., including local subsidence) for vulnerability assessment and adaptation planning.

Generally, quantitative predictions of future coastal change remain difficult despite the application of improvements in technology—for example, aerial photographs, satellite imagery, Light Detection And Ranging (LiDAR; Sesil et al., 2009; Revell et al., 2011; Pe'eri and Long, 2012)—to investigate and characterize large-scale shoreline changes. There is incomplete understanding of coastal changes over the decade and century time scales (Woodroffe and Murray-Wallace, 2012). Shoreline response is more complex than simple submergence because of factors such as sediment supply, mobilization and storage, offshore geology, engineering structures, and wave forcing (Ashton et al., 2011). The projection of the future impacts of climate change on natural systems is often hampered by the lack of sufficiently detailed data at the required levels of space and time. Although observations have been made on impacts on beaches, rocky coasts, wetlands, coastal aquifers, delta areas, or river mouths by multi-drivers of climate and human-induced origin, there is still an incomplete understanding of the relative role played by each of these drivers and, especially of their combined effect. Uncertainties are even higher when it comes to the evaluation of projected impacts.

For coastal ecosystems, more work needs to be done to develop predictive models based on findings from multi-stressor experiments, both in the field and in the laboratory. Reliable predictions require information on multifactorial experiments performed on communities (preferably in the field), and on time scales of months to years in order to take into consideration the processes of biological acclimation and adaptation.

Although sea level is projected to rise in the future, there are significant gaps in vulnerability assessment of other specific coastal impacts. For example, the modeling of diseases that could affect coastal areas is based mainly on the mean values of climate. Also, despite tourism being one of the most important industries in the coastal areas, not enough is known about tourists' reactions to projected climatic change (Moreno and Amelung, 2009b) or required adaptation measures for port facilities (UNCTAD, 2009).

A wide range of coastal management frameworks and measures is available and used in coastal adaptation to climate change, and the scope for their integration has increased by combining scenarios of climate change and socioeconomic conditions and risk assessment (Kirshen et al., 2012). While various adaptation measures are available, at the local level, there remains insufficient information on assessment of adaptation options, particularly in developing countries.

Data and knowledge gaps exist or their reliability is insufficient. Despite the availability of potentially useful climate information, a gap exists between what is useful information for scientists and for decision makers. For example, at the project level, engineers may have difficulties to "plug in" climate projections presented by scientists. The proposed actions to improve usability include varying levels of interaction, customization, value-adding, retailing, and wholesaling (Lemos et al., 2012) so that data and methods can be more openly accessible to fellow scientists, users, and the public (Kleiner, 2011).

Coastal systems are affected by human and climate drivers and there are also complex interactions between the two. In general, certain components of coastal systems are sensitive and attributable to climate drivers while others are not clearly discernible. For example, data are available on the range shift in coastal plant and animal species and the role of higher temperatures on coral bleaching (see Box CC-CR). However, in many cases in the human systems, the detectable changes can be largely attributed to human drivers (Section 5.3.4). Reducing our knowledge gaps on the understanding of the processes inducing changes would help to respond to them more efficiently.

The economics of coastal adaptation are under-researched. More comprehensive assessments of valuation of coastal ecosystem services,

adaptation costs, and benefits that simultaneously consider both the gradual impact of land loss due to sea level rise and the stochastic impacts of extreme water levels (storm surges, cyclones) are needed, as well as other impacts such as saltwater intrusion, wetlands loss and change, and backwater effects. Assessments should also consider a more comprehensive range of adaptation options and strategies, including "soft" protection, accommodation, and retreat options as well as the trade-offs between these.

Governance of coastal adaptation and the role of institutions in the transition toward sustainable coasts are under-researched. While institutional factors are recognized to be decisive in constraining and enabling coastal adaptation, most work remains descriptive. There is a great need for dedicated social science research aimed at understanding institutional change and which institutional arrangements are effective in which socioeconomic and biophysical contexts (Kay, 2012; see also Sections 5.5.3, 5.5.4).

Developing a coastal adaptation knowledge network between scientists, policymakers, stakeholders, and the general public could be considered a priority area for large coastal areas or regional areas affected by climate change and sea level rise. This is well developed in the USA, European Union, the Mediterranean, and Australia but less so in the developing countries, except in certain regions, for example, Caribbean islands and the Pacific Islands.

Future research needs for coastal adaptation are identified by several developments in climate science. Based on the Li et al. (2011) survey of the foci of climate research in the 21st century, the implications for coasts would be on biodiversity and flooding. Future technological advances may be significant—for example, new forms of energy and food production and information and communication technology (ICT) for risk monitoring (Delta Commission, 2008; Campbell et al., 2009; Zevenbergen et al., 2013)—and these would be useful for flood risks and food production in deltas and coastal systems (aquaculture).

With recent adverse climatic and environmental events on coasts, adaptation demands different decision regimes (Kiker et al., 2010) but adaptation, mitigation, and avoidance measures still require integrating research that includes natural and social sciences (CCSP, 2009). Although many gaps still remain, there is nevertheless a greater foundation of climate change research on coasts across a wide range of fields (Grieneisen and Zhang, 2011) upon which scientists, policymakers, and the public may find improved solutions for coastal adaptation.

References

Aargaard, T., J. Nielsen, S.G. Jensen, and J. Friderichsen, 2004: Longshore sediment transport and coastal erosion at Skallingen, Denmark. *Danish Journal of Geography,* **104(1)**, 5-14.

Abel, N., R. Gorddard, B. Harman, A. Leitch, J. Langridge, A. Ryan, and S. Heyenga, 2011: Sea level rise, coastal development and planned retreat: analytical framework, governance principles and an Australian case study. *Environmental Science and Policy,* **14(3)**, 279-288.

Adam, J.C., A.F. Hamlet, and D.P. Lettenmaier, 2009: Implications of global climate change for snowmelt hydrology in the twenty-first century. *Hydrological Processes*, **23(7)**, 962-972.

Aerts, J.C.J.H., W.J.W. Botzen, H. de Moel, and M. Bowman, 2013: Cost estimates for flood resilience and protection strategies in New York City. *Annals of the New York Academy of Sciences*, **1294**, 1-104.

Ahammad, R., 2011: Constraints of pro-poor climate change adaptation in Chittagong City. *Environment and Urbanization*, **23(2)**, 503-515.

Ahmed, A.U., 2005: Adaptation options for managing water related extreme events under climate change regime: Bangladesh perspectives. In *Climate Change and Water Resources in South Asia* [Mirza, M.M.Q. and Q.K. Ahmad (eds.)]. Balkema Press, Leiden, Netherlands, pp. 255-278.

Ahmed, A.U. (ed.), 2010: *Reducing Vulnerability to Climate Change: The Pioneering Example of Community Based Adaptation in Bangladesh*. Centre for Global Change (CGC) and CARE Bangladesh, Dhaka, Bangladesh, 23 pp.

Albright, R., 2011: Reviewing the effects of ocean acidification on sexual reproduction and early life history stages of reef-building corals. *Journal of Marine Biology*, **2011**, 473615, doi:10.1155/2011/473615.

Alexander, R.B., R.A. Smith, G.E. Schwarz, E.W. Boyer, J.V. Nolan, and J.W. Brakebill, 2008: Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River Basin. *Environmental Science and Technology*, **42(3)**, 822-830.

Alexandre, A., J. Silva, P. Buapet, M. Björk, and R. Santos, 2012: Effects of CO_2 enrichment on photosynthesis, growth, and nitrogen metabolism of the seagrass *Zostera noltii*. *Ecology and Evolution*, **2(10)**, 2625-2635.

Alongi, D. M., 2002: Present state and future of the world's mangrove forests. *Environmental Conservation*, 2**9(3)**, 331-349.

Alongi, D. M., 2008: Mangrove forests: resilience, protection from tsunamis, and response to global climate change. *Estuarine, Coastal and Shelf Science*, **76(1)**, 1-13.

Alvarez-Diaz, M., M.S.O. Giraldez, and M. Gonzalez-Gomez, 2010: Statistical relationships between the North Atlantic Oscillation and international tourism demand in the Balearic Islands, Spain. *Climate Research*, **43**, 207-214.

Andersson, A.J. and D. Gledhill, 2013: Ocean acidification and coral reefs: effects on breakdown, dissolution, and net ecosystem calcification. *Annual Review of Marine Science*, **5**, 321-348.

Andersson, A.J., F.T. Mackenzie, and J.-P. Gattuso, 2011: Effects of ocean acidification on benthic processes, organisms, and ecosystems. In: *Ocean Acidification* [Gattuso, J.-P. and L. Hansson (eds.)]. Oxford University Press, Oxford, UK, and New York, NY, USA, pp. 122-153.

Anthoff, D., R.J. Nicholls, and R.S.J. Tol, 2010: The economic impact of substantial sea-level rise. *Mitigation and Adaptation Strategies for Global Change*, **15(4)**, 321-335.

Anthony, A., J. Atwood, P. August, C. Byron, S. Cobb, C. Foster, C. Fry, A. Gold, K. Hagos, L. Heffner, D.Q. Kellogg, K. Lellis-Dibble, J.J. Opaluch, C. Oviatt, A. Pfeiffer-Herbert, N. Rohr, L. Smith, T. Smythe, J. Swift, and N. Vinhateiro, 2009: Coastal lagoons and climate change: ecological and social ramifications in U.S. Atlantic and Gulf Coast ecosystems. *Ecology and Society*, **14(1)**, 8, www.ecologyand society.org/vol14/iss1/art8/.

Anthony, K.R.N., D.L. Kline, G. Diaz-Pulido, S. Dove, and O. Hoegh-Guldberg, 2008: Ocean acidification causes bleaching and productivity loss in coral reef builders. *Proceedings of the National Academy of Sciences of the United States of America*, **105(45)**, 17442-17446.

Arkema, K.K., G. Guannel, G. Verutes, S.A. Wood, A. Guerry, M. Ruckelshaus, P. Kareiva, M. Lacayo, and J.M. Silver, 2013: Coastal habitats shield people and property from sea-level rise and storms. *Nature Climate Change*, **3(10)**, 913-918.

Arnell, N., T.K.T. Carter, K. Ebi, J. Edmonds, S. Hallegatte, E. Kriegler, R. Mathur, B. O'Neill, K. Riahi, H. Winkler, D. van Vuuren, and T. Zwickel, 2011: *A Framework for a New Generation of Socioeconomic Scenarios for Climate Change Impact, Adaptation, Vulnerability, and Mitigation Research.* Primary background document for the workshop, "The Nature and Use of New Socioeconomic Pathways for Climate Change Research," Nov. 2-4, 2011, hosted by the Integrated Science Program, National Center for Atmospheric Research (NCAR), Mesa Laboratory, Boulder, CO, USA, 42 pp., www.isp.ucar.edu/sites/default/files/Scenario_FrameworkPaper_15aug11_1.pdf

Arnell, N.W., J.A. Lowe, S. Brown, S.N. Gosling, P. Gottschalk, J. Hinkel, B. Lloyd-Hughes, R.J. Nicholls, T.J. Osborn, T.M. Osborne, G.A. Rose, P. Smith, and R.F. Warren, 2013: A global assessment of the effects of climate policy on the impacts of climate change. *Nature Climate Change*, **3(5)**, 512-519.

Ashton, A.D., M.J.A. Walkden, and M.E. Dickson, 2011: Equilibrium response of cliffed coasts to changes in the rate of sea level rise. *Marine Geology*, **284(1-4)**, 217-229.

Aufdenkampe, A.K., E. Mayorga, P.A. Raymond, J.M. Melack, S.C. Doney, S.R. Alin, R.E. Aalto, and K. Yoo, 2011: Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. *Frontiers in Ecology and the Environment,* **9(1)**, 53-60.

Ayers, J. and D. Dodman, 2010: Climate change adaptation and development: the state of the debate. *Progress in Development Studies*, **10(2)**, 161-168.

Ayers, J. and T. Forsyth, 2009: Community-based adaptation to climate change: strengthening resilience through development. *Environment*, **51(4)**, 22-31.

Ayers, J. and S. Huq, 2009: Supporting adaptation through development: what role for official development assistance? *Development Policy Review*, **27(6)**, 675-692.

Ayers, J. and S. Huq, 2013: Adaptation, development and the community. In: *Climate Adaptation Futures* [Palutikof, J., S.L. Boulter, A.J. Ash, M.S. Smith, M. Parry, M. Waschka, and D. Guitart (eds.)]. 1st edn., Wiley-Blackwell, London, UK, pp. 203-214.

Badjeck, M.C, E.H. Allison, A.S. Halls, and N.K. Dulvy, 2010: Impacts of climate variability and change on fishery-based livelihoods. *Marine Policy*, **34(3)**, 375-383.

Bagstad, K.J., K. Stapleton, and J.R. D'Agostino, 2007: Taxes, subsidies, and insurance as drivers of United States coastal development. *Ecological Economics,* **63(2-3)**, 285-298.

Baker, A.C., P.W. Glynn, and B. Riegl, 2008: Climate change and coral reef bleaching: an ecological assessment of long-term impacts, recovery trends and future outlook. *Estuarine, Coastal and Shelf Science*, **80(4)**, 435-471.

Baker-Austin, C., J.A. Trinanes, N.G.H. Taylor, R. Hartnell, A. Siitonen, and J. Martinez-Urtaza, 2013: Emerging *Vibrio* risk at high latitudes in response to ocean warming. *Nature Climate Change*, **3(1)**, 73-77.

Barange, M. and R.I. Perry, 2009: Physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture. In: *Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge* [Cochrane, K., C. De Young, D. Soto, and T. Bahri (eds.)]. FAO Fisheries and AquacultureTechnical Paper No. 530, Food and Agricultural Organization of the United Nations (FAO), Rome, Italy, pp. 7-106.

Barbier, E.B., E.W. Koch, B.R. Silliman, S.D. Hacker, E. Wolanski, J. Primavera, E.F. Granek, S. Polasky, S. Aswani, L.A. Cramer, D.M. Stoms, C.J. Kennedy, D. Bael, C.V. Kappel, G.M.E. Perillo, and D.J. Reed, 2008: Coastal ecosystem-based management with nonlinear ecological functions and values. *Science*, **319(5861)**, 321-323.

Barbier, E.B., S.D. Hacker, C. Kennedy, E.W. Koch, A.C. Stier, and B.R. Silliman, 2011: The value of estuarine and coastal ecosystem services. *Ecological Monographs*, **81(2)**, 169-193.

Barlow, P. and E. Reichard, 2010: Saltwater intrusion in coastal regions of North America. *Hydrogeology Journal*, **18(1)**, 247-260.

Barras, J.A., J.C. Bernier, and R.A. Morton, 2008: *Land Area Change in Coastal Louisiana: A Multidecadal Perspective (from 1956 to 2006)*. Pamphlet to accompany U.S. Geological Survey Scientific Investigations Map 3019, scale 1:250,000, USGS, Reston, VA, USA, 14 pp.

Barry, J.P., S. Widdicombe, and J. Hall-Spencer, 2011: Effects of ocean acidification on marine biodiversity and ecosystem function. In: *Ocean Acidification* [Gattuso, J.-P. and L. Hansson (eds.)]. Oxford University Press, Oxford, UK, pp. 192-209.

Barton, A., B. Hales, G.G. Waldbusser, C. Langdon, and R.A. Feely, 2012: The Pacific oyster, *Crassostrea gigas*, shows negative correlation to naturally elevated carbon dioxide levels: implications for near-term ocean acidification effects. *Limnology and Oceanography*, **57(3)**, 698-710.

Baulcomb, C., 2011: *Review of the Evidence Linking Climate Change to Human Health for Eight Diseases of Tropical Importance*. Land Economy Working Paper No. 63, Scottish Agricultural College, Edinburgh, UK, 45 pp.

Beck, M.W., R.D. Brumbaugh, L. Airoldi, A. Carranza, L.D. Coen, C.C.O. Defeo, G.J. Edgar, B. Hancock, M.C. Kay, H.S. Lenihan, M.W. Luckenbach, C.L. Toropova, G. Zhang, and X. Guo, 2011: Oyster reefs at risk and recommendations for conservation, restoration and management. *BioScience*, **61(2)**, 107-116.

Becker, A., S. Inoue, M. Fischer, and B. Schwegler, 2012: Climate change impacts on international seaports: knowledge, perceptions and planning efforts among port administrators. *Climatic Change*, **110(1-2)**, 5-29.

Becker, A.H., M. Acciaro, R. Asariotis, E. Cabrera, L. Cretegny, P. Crist, M. Esteban, A. Mather, S. Messner, S. Naruse, A.K.Y. Ng, S. Rahmstorf, M. Savonis, D.-W. Song, V. Stenek, and A.F. Velegrakis, 2013: A note on climate change adaptation for seaports: a challenge for global ports, a challenge for global society. *Climatic Change*, **120(4)**, 683-695.

Bedsworth, L.W. and E. Hanak, 2010: Adaptation to climate change. *Journal of the American Planning Association*, **76(4)**, 477-495.

Bell, J.D., M. Kronen, A. Vunisea, W.J. Nash, G. Keeble, A. Demmke, S. Pontifex, and S. Andréfouët, 2009: Planning the use of fish for food security in the Pacific. *Marine Policy*, **33(1)**, 64-76.

Bell, J.D., A. Ganachaud, P.C. Gehrke, S.P. Griffiths, A.J. Hobday, O. Hoegh-Guldberg, J.E. Johnson, R. Le Borgne, P. Lehodey, J.M. Lough, R.J. Matear, T.D. Pickering, M.S. Pratchett, A.S. Gupta, I. Senina, and M. Waycott, 2013: Mixed responses of tropical Pacific fisheries and aquaculture to climate change. *Nature Climate Change*, **3(6)**, 591-599.

Berkes, F. and C. Folke (eds.), 1998: *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience.* Cambridge University Press, Cambridge, UK and New York, NY, USA, 459 pp.

Bernie, D., J. Lowe, T. Tyrrell, and O. Legge, 2010: Influence of mitigation policy on ocean acidification. *Geophysical Research Letters*, **37(15)**, L15704, doi:10.1029/2010GL043181.

Betts, R.A., O. Boucher, M. Collins, P.M. Cox, P.D. Falloon, N. Gedney, and D.L. Hemming, 2007: Projected increase in continental runoff due to plant responses to increasing carbon dioxide. *Nature*, **448(7157)**, 1037-1041.

Biesbroek, G.R., R.J. Swart, T.R. Carter, C. Cowan, T. Henrichs, H. Mela, M.D. Morecroft, and D. Rey, 2010: Europe adapts to climate change: comparing National Adaptation Strategies. *Global Environmental Change: Human and Policy Dimensions*, **20(3)**, 440-450.

Biggs, D., 2011: *Case Study: the Resilience of the Nature-based Tourism System on Australia's Great Barrier Reef*. Report prepared for the Australian Department of Sustainability, Environment, Water, Population and Communities on behalf of the State of the Environment 2011 Committee. Canberra, Australia, 32 pp.

Bird, E.C.F., 2000: *Coastal Geomorphology: An Introduction*. John Wiley & Sons, Chichester, UK and Hoboken, NJ, USA, 411 pp.

Bjarnadottir, S., Y. Li, and M.G. Stewart, 2011: Social vulnerability index for coastal communities at risk to hurricane hazard and a changing climate. *Natural Hazards*, **59(2)**, 1055-1075.

Black, R., W.N. Adger, N.W. Arnell, S. Dercon, A. Geddes, and D.S.G. Thomas, 2011: The effect of environmental change on human migration. *Global Environmental Change: Human and Policy Dimensions*, **21(1)**, S3-S11.

Boateng, I., 2010: *Spatial Planning in Coastal Regions: Facing the Impact of Climate Change*. FIG Publication No. 55, International Federation of Surveyors (FIG), Copenhagen, Denmark, 60 pp.

Boateng, I., 2012: GIS assessment of coastal vulnerability to climate change and coastal adaption planning in Vietnam. *Journal of Coastal Conservation*, **16**, 25-36.

Boden, T., G. Marland, and B. Andres, 2011: *Global CO_2 Emissions from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751-2008*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN, USA, emissions data available at: cdiac.ornl.gov/ftp/ndp030/global.1751_2008.ems.

Boehlert, G.W. and A.B. Gill, 2010: Environmental and ecological effects of ocean renewable energy development. *Oceanography*, **23(2)**, 68-81.

Bollmann, M., T. Bosch, F. Colijn, R. Ebinghaus, R. Froese, K. Güssow, S. Khalilian, S. Krastel, A. Körtzinger, M. Langenbuch, M. Latif, B. Matthiessen, F. Melzner, A. Oschlies, S. Petersen, A. Proelß, M. Quaas, J. Reichenbach, T. Requate, T. Reusch, P. Rosenstiel, J.O. Schmidt, K. Schrottke, H. Sichelschmidt, U. Siebert, R. Soltwedel, U. Sommer, K. Stattegger, H. Sterr, R. Sturm, T. Treude, A. Vafeidis, C. van Bernem, J. van Beusekom, R. Voss, M. Visbeck, M. Wahl, K. Wallmann, and F. Weinberger, 2010: *World Ocean Review 2010*. Maribus, Hamburg, Germany, 232 pp.

Borges, A.V., 2005: Do we have enough pieces of the jigsaw to integrate CO_2 fluxes in the coastal ocean? *Estuaries*, **28(1)**, 3-27.

Borges, A.V., 2011: Present day carbon dioxide fluxes in the coastal ocean and possible feedbacks under global change. In: *Oceans and the Atmospheric Carbon Content* [da Silva Duarte, P.M. and J.M. Santana-Casiano (eds.)]. Springer, Dordrecht, Netherlands, pp. 47-77.

Borges, A.V. and G. Abril, 2011: Carbon dioxide and methane dynamics in estuaries. In: *Treatise on Estuarine and Coastal Science: Vol. 5: Biogeochemistry* [Wolanski, E. and D. McLusky (eds.)]. Academic Press, Waltham, MA, USA, pp. 119-161.

Borges, A.V. and N. Gypens, 2010: Carbonate chemistry in the coastal zone responds more strongly to eutrophication than to ocean acidification. *Limnology and Oceanography*, **55(1)**, 346-353.

Bormann, H., F. Ahlhorn, and T. Klenke, 2012: Adaptation of water management to regional climate change in a coastal region – hydrological change vs. community perception and strategies. *Journal of Hydrology*, **454-455**, 64-75.

Borsje, B.W, B.K. van Wesenbeeck, F. Dekker, P. Paalvast, T.J. Bouma, M.M. van Katwijk, and M. de Vries, 2011: How ecological engineering can serve in coastal protection. *Ecological Engineering*, **37**, 113-122.

Bosom, E. and J.A. Jimenez, 2011: Probabilistic coastal vulnerability assessment to storms at regional scale–application to Catalan beaches (NW Mediterranean). *Natural Hazards and Earth System Sciences*, **11(2)**, 475-484.

Bougherara, D., G. Grolleau, and N. Mzoughi, 2009: The 'make or buy' decision in private environmental transactions. *European Journal of Law Economics*, **27**, 79-99.

Bouwman, A.F., A.H.W. Beusen, and G. Billen, 2009: Human alteration of the global nitrogen and phosphorus soil balances for the period 1970-2050. *Global Biogeochemical Cycles*, **23(4)**, GB0A04, doi:10.1029/2009GB003576.

Breitburg, D.L., D.W. Hondorp, L.A. Davias, and R.J. Diaz, 2009: Hypoxia, nitrogen, and fisheries: integrating effects across local and global landscapes. *Annual Reviews of Marine Science*, **1**, 329-349.

Briggs, R.W., K. Sieh, A.J. Meltzner, D. Natawidjaja, J. Galetzka, B. Suwargadi, Y. Hsu, M. Simons, N. Hananto, I. Suprihanto, D. Prayudi, J. Avouac, L. Prawirodirdjo, and Y. Bock, 2006: Deformation and slip along the Sunda Megathrust in the Great 2005 Nias-Simeulue Earthquake. *Science*, **311(5769)**, 1897-1901.

Brooks, S.M. and T. Spencer, 2013: Importance of decadal scale variability in shoreline response: examples from soft rock cliffs, East Anglian coast, UK. *Journal of Coastal Conservation*, doi:10.1007/s11852-013-0279-7.

Brown, B.E., R.P. Dunne, N. Phongsuwan, and P.J. Somerfield, 2011: Increased sea level promotes coral cover on shallow reef flats in the Andaman Sea, eastern Indian Ocean. *Coral Reefs*, **30**, 867-878.

Brown, K., E.L. Tompkins, and W.N. Adger, 2002: *Making Waves: Integrating Coastal Conservation and Development*. Earthscan, London, UK, 164 pp.

Brown, S., M. Barton, and R.J. Nicholls, 2013: Shoreline response of eroding soft cliffs due to hard defenses. *Proceedings of the Institution of Civil Engineers: Maritime Engineering*, doi:10.1680/11.00026.

Bruun, P., 1962: Sea-level rise as a cause of shore erosion. *Journal of the Waterways and Harbors Division: Proceedings of the American Society of Civil Engineers*, **88**, 117-130.

Buddemeier, R.W. and S.V. Smith, 1988: Coral reef growth in an era of rapidly rising sea level: predictions and suggestions for long-term research. *Coral Reefs*, **7**, 51-56.

Bunce, M., K. Brown, and S. Rosendo, 2010: Policy misfits, climate change and cross-scale vulnerability in coastal Africa: how development projects undermine resilience. *Environmental Science and Policy*, **13(6)**, 485-497.

Burch, S., 2010: Transforming barriers into enablers of action on climate change: insights from three municipal case studies in British Columbia, Canada. *Global Environmental Change*, **20(2)**, 287-297.

Burke, L.M., K. Reytar, M. Spalding, and A. Perry, 2011: *Reefs at Risk Revisited.* World Resources Institute, Washington, DC, USA, 114 pp.

Burrows, M.T., D.S. Schoeman, L.B. Buckley, P. Moore, E.S. Poloczanska, K.M. Brander, C. Brown, J.F. Bruno, C.M. Duarte, B.S. Halpern, J. Holding, C.V. Kappel, W. Kiessling, M.I. O'Connor, J.M. Pandolfi, C. Parmesan, F.B. Schwing, W.J. Sydeman, and A.J. Richardson, 2011: The pace of shifting climate in marine and terrestrial ecosystems. *Science*, **334(6056)**, 652-655.

Cai, W., X. Hu, W. Huang, M.C. Murrell, J.C. Lehrter, S.E. Lohrenz, W. Chou, W. Zhai, J.T. Hollibaugh, Y. Wang, P. Zhao, X. Guo, K. Gundersen, M. Dai, and G. Gong, 2011: Acidification of subsurface coastal waters enhanced by eutrophication. *Nature Geoscience*, **4**, 766-770.

Callaway, R., A.P. Shinn, S.E. Grenfell, J.E. Bron, G. Burnell, E.J. Cook, M. Crumlish, S. Culloty, K. Davidson, R.P. Ellis, J. Flynn, C. Fox, D.M. Green, G.C. Hays, A.D. Hughes, E. Johnston, C.D. Lowe, I. Lupatsch, S. Malham, A.F. Mendzil, T. Nickell, T. Pickerell, A.F. Rowley, M.S. Stanley, D.R. Tocher, J.F. Turnbull, G. Webb, E. Wootton, and R.J. Shields, 2012: Review of climate change impacts on marine aquaculture in the UK and Ireland. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **22(3)**, 389-421.

Cambers, G., 2009: Caribbean beach changes and climate change adaptation. *Aquatic Ecosystem Health and Management*, **12**, 168-176.

Camoin, G.F., C. Seard, P. Deschamps, J.M. Webster, E. Abbey, J.C. Braga, Y. Iryu, N. Durand, E. Bard, B. Hamelin, Y. Yokoyama, A.L. Thomas, G.M. Henderson, and P. Dussouillez, 2012: Reef response to sea-level and environmental changes during the last deglaciation: integrated Ocean Drilling Program Expedition 310, Tahiti Sea Level. *Geology*, **40(7)**, 643-646.

Campbell, A., V. Kapos, A. Chenery, N. Doswald, S.I. Kahn, M. Rashid, J. Scharlemann, and B. Dickson, 2009. The linkages between biodiversity and climate change adaptation – a review of the recent scientific literature. In : *Review of the Literature on the Links between Biodiversity and Climate Change: Impacts, Adaptation and Mitigation* [Campbell, A., V. Kapos, J.P.W. Scharlemann, P. Bubb, A. Chenery, L. Coad, B. Dickson, N. Doswald, M.S.I. Khan, F. Kershaw, and M. Rashid (eds.)]. Technical Series No. 42, Secretariat of the Convention on Biological Diversity, Montreal, Canada, pp. 49-87.

Canu, D.M., C. Solidoro, G. Cossarini, and F. Giorgi, 2010: Effect of global change on bivalve rearing activity and the need for adaptive management. *Climate Research*, **42(1)**, 13-26.

Canuel, E.A., S.S. Cammer, H.A. McIntosh, and C.R. Pondell, 2012: Climate change impacts on the organic carbon cycle at the land-ocean interface. *Annual Review of Earth and Planetary Sciences*, **40(1)**, 685-711.

CCSP, 2009: *Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region* [Titus, J.G. (Coordinating Lead Author), K.E. Anderson, D.R. Cahoon, D.B. Gesch, S.K. Gill, B.T. Gutierrez, E.R. Thieler, and S.J.Williams (Lead Authors)]. Report by the U.S. Climate Change Science Program (CCSP) and the Subcommittee on Global Change Research, Synthesis and Assessment Product 4.1, U.S. Environmental Protection Agency, Washington, DC, USA, 320 pp.

Celliers, L., S. Rosendo, I. Coetzee, and G. Daniels, 2013: Pathways of integrated coastal management from national policy to local implementation: enabling climate change adaptation. *Marine Policy*, **39**, 72-86.

Central Disaster Management Council, 2011: *Report of the Committee for Technical Investigation on Countermeasures for Earthquakes and Tsunamis Based on the Lessons Learned from the "2011 off the Pacific coast of Tohoku Earthquake"*. Cabinet Office, Government of Japan, Tokyo, Japan, 46 pp., www.bousai.go.jp/jishin/chubou/higashinihon/Report.pdf

Chaibi, M. and M. Sedrati, 2009: Coastal erosion induced by human activities: the case of two embayed beaches on the Moroccan coast. *Journal of Coastal Research*, **SI 56**, 1184-1188.

Chen, C.-C., B. McCarl, and C.-C. Chang, 2012: Climate change, sea level rise and rice: global market implications. *Climatic Change*, **110(3-4)**, 543-560.

Chen, C.-T.A. and A.V. Borges, 2009: Reconciling opposing views on carbon cycling in the coastal ocean: continental shelves as sinks and near-shore ecosystems as sources of atmospheric CO_2. *Deep-Sea Research II*, **56**, 578-590.

Cheong, S.-M., B. Silliman, P.P. Wong, B. van Wesenbeeck, C.-K. Kim, and G. Guannel, 2013: Coastal adaptation with ecological engineering. *Nature Climate Change*, **3(9)**, 787-791.

Cheung, W.W.L., V.W.Y. Lam, J.L. Sarmiento, K. Kearney, R. Watson, and D. Pauly, 2009: Projecting global marine biodiversity impacts under climate change scenarios. *Fish and Fisheries*, **10**, 235-251.

Cheung, W.W.L., V.W.Y Lam, J.L. Sarmiento, K. Kearney, R. Watson, D. Zeller, and D. Pauly, 2010: Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology*, **16**, 24-35.

Chisolm, E.I. and J.C. Matthews, 2012: Impact of hurricanes and flooding on buried infrastructure. *Leadership and Management in Engineering*, **12(3)**, 151-156.

Chou, W.-C., J.-L. Wu, Y.-C. Wang, H. Huang, F.-C. Sung, and C.-Y. Chuang, 2010: Modeling the impact of climate variability on diarrhea-associated diseases in Taiwan (1996-2007). *Science of The Total Environment*, **409(1)**, 43-51.

Christie, P., K. Lowry, A.T. White, E.G. Oracion, L. Sievanen, R.S. Pomeroy, R.B. Pollnac, J.M. Patlis, and R.-L.V. Eisma, 2005: Key findings from a multidisciplinary examination of integrated coastal management process sustainability. *Ocean and Coastal Management*, **48 (3-6)**, 468-483.

Chu, Z.X., X.G. Sun, S.K. Zhai, and K.H. Xu, 1996: Changing pattern of accretion/erosion of the modern Yellow River (Huanghe) subaerial delta, China: based on remote sensing images. *Marine Geology*, **227**, 13-30.

Cinner, J.E., T.R. McClanahan, N.A.J. Graham, T.M. Daw, J. Maina, S.M. Stead, A. Wamukota, K. Brown, and Ö. Bodin, 2012: Vulnerability of coastal communities to key impacts of climate change on coral reef fisheries. *Global Environmental Change*, **22(1)**, 12-20.

Cloern, J.E. and A.D. Jassby, 2008: Complex seasonal patterns of primary producers at the land-sea interface. *Ecology Letters*, **11(12)**, 1294-1303.

Colberg, F. and K.L. McInnes, 2012: The impact of storminess changes on extreme sea levels over southern Australia. *Journal of Geophysical Research-Oceans*, **117(C8)**, C08001, doi:10.1029/2012JC007919.

Comeaux, R.S., M.A. Allison, and T.S. Bianchi, 2011: Mangrove expansion in the Gulf of Mexico with climate change: implications for wetland health and resistance to rising sea levels. *Estuarine, Coastal and Shelf Science*, **96(1)**, 81-95.

Committee on Adaptation Strategy for Global Warming in the Coastal Zone, 2011: *Manual for Adapting to Global Warming Concurrently with Renewal of Coastal Structures* (interim version). Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Tokyo, Japan, 50 pp. (in Japanese).

Cooper, J.A.G. and O.H. Pilkey, 2004: Sea-level rise and shoreline retreat: time to abandon the Bruun Rule. *Global and Planetary Change*, **43(3-4)**, 157-171.

Cooper, T.F., R.A. O'Leary, and J.M. Lough, 2012: Growth of Western Australian corals in the Anthropocene. *Science,* **335(6068)**, 593-596.

Costanza, R., F.H. Sklar, and M.L. White, 1990: Modeling coastal landscape dynamics. *Bioscience*, **40(2)**, 91-107.

Couce, E., P.J. Irvine, L.J. Gregorie, A. Ridgwell, and E.J. Hendy, 2013: Tropical coral reef habitat in a geoengineered, high-CO_2 world. *Geophysical Research Letters*, **40**,1799-1804.

Coumou, D. and S. Rahmstorf, 2012: A decade of weather extremes. *Nature Climate Change*, **2(7)**, 491-496.

Craft, C., J. Clough, J. Ehman, S. Joye, R. Park, S. Pennings, H. Guo, and M. Machmuller, 2009: Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services. *Frontiers in the Ecology and Environment*, **7**, 73-78.

Crain, C.M., B.S. Halpern, M.W. Beck, and C.V. Kappel, 2009: Understanding and managing human threats to the coastal marine environment. *Year in Ecology and Conservation Biology*, **1162**, 39-62.

Dai A., T. Qian, K.E. Trenberth, and J.D. Milliman, 2009: Changes in continental freshwater discharge from 1948 to 2004. *Journal of Climate*, **22**, 2773-2792.

Dasgupta, S., B. Laplante, C. Meisner, D. Wheeler, and J. Yan, 2009: The impact of sea level rise on developing countries: a comparative analysis. *Climatic Change*, **93(3-4)**, 379-388.

Dasgupta, S., B. Laplante, S. Murray, and D. Wheeler, 2011: Exposure of developing countries to sea-level rise and storm surges. *Climatic Change*, **106**, 567-579.

Davis Jr., R.A. and D.M. FitzGerald, 2004: *Beaches and Coasts*. Blackwell Publishing, Oxford, UK, 432 pp.

Daw, T., W.N. Adger, and K. Brown, 2009: Climate change and capture fisheries: potential impacts, adaptation and mitigation. In: *Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge* [Cochrane, K., C. De Young, D. Soto, and T. Bahri (eds.)]. FAO Fisheries and Aquaculture Technical Paper No 530, Food and Agricultural Organization of the United Nations (FAO), Rome, Italy, pp.107-150.

Dawson, R.J., M.E. Dickson, R.J. Nicholls, J.W. Hall, M.J.A. Walkden, P.K. Stansby, M. Mokrech, J. Richards, J. Zhou, J. Milligan, A. Jordan, S. Pearson, J. Rees, P.D. Bates, S. Koukoulas, and A.R. Watkinson, 2009: Integrated analysis of risks of coastal flooding and cliff erosion under scenarios of long term change. *Climatic Change*, **95**, 249-288.

Day, J.W. and L. Giosan, 2008: Survive or subside? *Nature Geoscience*, **1**, 156-157.

Day, J.W., C. Ibáñez, F. Scarton, D. Pont, P. Hensel, J. Day, and R. Lane, 2011: Sustainability of Mediterranean deltaic and lagoon wetlands with sea-level rise: the importance of river input. *Estuaries and Coasts*, **34**, 483-493.

De Bie, M.J.M., J.J. Middelburg, M. Starink, and H.J. Laanbroek, 2002: Factors controlling nitrous oxide at the microbial community and estuarine scale. *Marine Ecology Progress Series*, **240**, 1-9.

De Sherbinin, A., M. Castro, F. Gemenne, M.M. Cernea, S. Adamo, P.M. Fearnside, G. Krieger, S. Lahmani, A. Oliver-Smith, A. Pankhurst, T. Scudder, B. Singer, Y. Tan, G. Wannier, P. Boncour, C. Ehrhart, G. Hugo, B. Pandey, and G. Shi, 2011: Preparing for resettlement associated with climate change. *Science*, **334(6055)**, 456-457.

De Silva, S.S. and D. Soto, 2009: Climate change and aquaculture: potential impacts, adaptation and mitigation. In: *Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge* [Cochrane, K., C. De Young, D. Soto, and T. Bahri (eds.)]. FAO Fisheries and Aquaculture Technical Paper No. 530, Food and Agricultural Organization of the United Nations (FAO), Rome, Italy, pp. 151-212.

De'ath, G., J.M. Lough, and K.E. Fabricius, 2009: Declining coral calcification on the Great Barrier Reef. *Science*, **323(5910)**, 116-119.

De'ath, G., K.E. Fabricius, H. Sweatman, and M. Puotinen, 2012: The 27-year declines of coral cover on the Great Barrier Reef and its causes. *Proceedings of the National Academy of Sciences of the U.S.Anited States of America*, **109(44)**, 17995-17999.

Debernard, J.B. and L.P. Røed, 2008: Future wind, wave and storm surge climate in the Northern Seas: a revisit. *Tellus A: Dynamic Meteorology and Oceanography*, **60(3)**, 427-438.

Delta Commission, 2008: *Working Together with Water: A Living Land Builds for its Future: Summary and Conclusions*. Deltacommissie, The Hague, Netherlands, 23 pp.

Dev, P., 2013: Waterlogging through soil-less agriculture as a climate resilient adaptation option. In: *Climate Change and Disaster Risk Management* [Filho, W.L. (ed.)]. Part 4, Climate Change Management Series, Springer-Verlag, Berlin Heidleberg, Germany, pp. 681-692.

Diaz, R.J. and R. Rosenberg, 2008: Spreading dead zones and consequences for marine ecosystems. *Science*, **321(5891)**, 926-929.

Díaz-Almela, E., N. Marbà, and C.M. Duarte, 2007: Consequences of Mediterranean warming events in seagrass (*Posidonia oceanica*) flowering records. *Global Change Biology*, **13**, 224-235.

Díaz-Almela, E., N. Marbà, R. Martínez, R. Santiago, and C.M. Duarte, 2009: Seasonal dynamics of *Posidonia oceanica* in Magalluf Bay (Mallorca, Spain): temperature effects on seagrass mortality. *Limnology and Oceanography*, **54**, 2170-2182.

Dietz, T., E. Ostrom, and P.C. Stern, 2003: The struggle to govern the commons. *Science*, **302(5652)**, 1907-1912.

Dodman, D. and D. Mitlin, 2011: Challenges to community-based adaptation. *Journal of International Development*, **25(5)**, 640-659.

Dokka, R.K., 2011: The role of deep processes in late 20th century subsidence of New Orleans and coastal areas of southern Louisiana and Mississippi. *Journal of Geophysical Research: Solid Earth*, **116**, B06403, doi:10.1029/2010JB008008.

Doney, S.C., N. Mahowald, I. Lima, R.A. Feely, F.T. Mackenzie, J. Lamarque, and P.J. Rasch, 2007: Impact of anthropogenic atmospheric nitrogen and sulfur deposition on ocean acidification and the inorganic carbon system. *Proceedings of the National Academy of Sciences of the United States of America*, **104(37)**, 14580-14585.

Dove, S.G., D.I. Kline, O. Pantos, F.E. Angly, G.W. Tyson, and O. Hoegh-Guldberg, 2013: Reef calcification versus decalcification: the difference between "reduced" and "business-as-usual" CO_2 emission scenarios. *Proceedings of the National Academy of Sciences of the United States of America*, **110(38)**, 15342-15347.

Duarte, C.M., J.J. Middelburg, and N. Caraco, 2005: Major role of marine vegetation on the oceanic carbon cycle. *Biogeosciences*, **2**, 1-8.

Duarte, C.M., I.E. Hendriks, T.S. Moore, Y.S. Olsen, A. Steckbauer, L. Ramajo, J. Carstensen, J.A. Trotter, and M. McCulloch, 2013a: Is ocean acidification an open-ocean syndrome? Understanding anthropogenic impacts on marine pH. *Estuaries and Coasts*, **36(2)**, 221-236.

Duarte, C.M., I.J. Losada, I.E. Hendriks, I. Mazarrasa, and N. Marbá, 2013b: The role of coastal plant communities for climate change adaptation and mitigation. *Nature Climate Change*, **3**, 961-968.

Duke, N.C., M.C. Ball, and J.C. Ellison, 1998: Factors influencing biodiversity and distributional gradients in mangroves. *Global Ecology and Biogeography Letters*, **7(1)**, 27-47.

Dullo, W.C., 2005: Coral growth and reef growth: a brief review. *Facies*, **51(1-4)**, 33-48.

Dulvy, N.K., S.I. Rogers, S. Jennings, V. Stelzenmüller, S.R. Dye, and H.R. Skjoldal, 2008: Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. *Journal of Applied Ecology*, **45(4)**, 1029-1039.

Eakin, C. M., J.A. Morgan, S.F. Heron, T.B. Smith, G. Liu, L. Alvarez-Filip, B. Baca, E. Bartels, C. Bastidas, C. Bouchon, M. Brandt, A.W. Bruckner, L. Bunkley-Williams, A. Cameron, B.D. Causey, M. Chiappone, T.R.L. Christensen, M.J.C. Crabbe, O. Day, E. de la Guardia, G. Diaz-Pulido, D. DiResta, D.L. Gil-Agudelo, D.S. Gilliam, R.N. Ginsburg, S. Gore, H.M. Guzmán, J.C. Hendee, E.A. Hernández-Delgado, E. Husain, C.F.G. Jeffrey, R.J. Jones, E. Jordán-Dahlgren, L.S. Kaufman, D.I. Kline, P.A. Kramer, J.C. Lang, D. Lirman, J. Mallela, C. Manfrino, J.-P. Maréchal, K. Marks, J. Mihaly, W.J. Miller, E.M. Mueller, E.M. Muller, C.A.O. Toro, H.A. Oxenford, D. Ponce-Taylor, N. Quinn, K.B. Ritchie, S. Rodríguez, A.R. Ramírez, S. Romano, J.F. Samhouri, J.A. Sánchez, G.P. Schmahl, B.V. Shank, W.J. Skirving, S.C.C. Steiner, E. Villamizar, S.M. Walsh, C. Walter, E. Weil, E.H. Williams, K.W. Roberson, and Y. Yusuf, 2010: Caribbean corals in crisis: record thermal stress, bleaching, and mortality in 2005. *PLoS ONE*, **5(11)**, e13969, doi:10.1371/journal.pone.0013969.

Ekstrom, J.A., S.C. Moser, and M. Torn, 2011: *Barriers to Adaptation: A Diagnostic Framework*. Public Interest Energy Research (PIER) Program Final Project Report, Contract No. CEC-500- 2011-004, California Energy Commission (CEC), Sacramento, CA, USA, 73 pp.

Engineers Australia, 2012: *Climate Change Adaptation Guidelines in Coastal Management and Planning.* The National Committee on Coastal and Ocean Engineering, Engineers Australia, EA Books, Engineers Media, Crow's Nest, New South Wales, Australia, 133 pp.

Environment Agency, 2012: *Managing Flood Risk through London and the Thames Estuary: TE2100 Plan*. Thames Estuary 2100, Environment Agency, London, UK, 230 pp.

EPA, 2009: *Synthesis of Adaptation Options for Coastal Areas*. U.S. Environmental Protection Agency (EPA), Climate Ready Estuaries Program, Washington DC, USA, 32 pp.

Erdner, D.L., J. Dyble, M.L. Parsons, R.C. Stevens, K.A. Hubbard, M.L. Wrabel, S.K. Moore, K.A, Lefebvre, D.M. Anderson, P. Bienfang, R.R. Bidigare, M.S. Parker, P. Moeller, L.E. Brand, and V.L. Trainer, 2008: Centers for Oceans and Human Health: a unified approach to the challenge of harmful algal blooms. *Environmental Health*, **7(Suppl 2)**, doi:10.1186/1476-069X-7-S2-S2.

Ericson, J.P., C.J. Vorosmarty, S.L. Dingman, L.G.Ward, and M. Meybeck, 2006: Effective sea-level rise and deltas: causes of change and human dimension implications. *Global Planet Change*, **50**, 63-82.

Espinosa-Romero, M.J., K.M.A. Chan, T. McDaniels, and D.M. Dalmer, 2011: Structuring decision-making for ecosystem-based management. *Marine Policy*, **35(5)**, 575-583.

Esteban, M., C. Webersik, and T. Shibayama, 2010: Methodology for the estimation of the increase in time loss due to future increase in tropical cyclone intensity in Japan. *Climate Change*, **102(3)**, 555-578.

Esteban, M., N.D. Thao, H. Tagaki, and T. Shibayama, 2012: Increase in port downtime and damage in Vietnam due to a potential increase in tropical cyclone intensity. In: *Climate Change and the Sustainable Use of Water Resources* [Filho, W.L. (ed.)]. Springer-Verlag, Berlin Heidelberg, Germany, pp. 101-125.

Falaleeva, M., C. O'Mahony, S. Gray, M. Desmond, J. Gault, and V. Cummins, 2011: Towards climate adaptation and coastal governance in Ireland: integrated architecture for effective management? *Marine Policy,* **35(6)**, 784-793.

FAO, 2010: *The State of World Fisheries and Aquaculture*. Food and Agricultural Organization of the United Nations (FAO), Rome, Italy, 197 pp.

FAO, 2012: *The State of World Fisheries and Aquaculture*. Food and Agricultural Organization of the United Nations (FAO), Rome, Italy, 209 pp.

Faulkner, L. and I. Ali, 2012: *Moving Towards Transformed Resilience: Assessing Community-based Adaptation in Bangladesh*. ActionAid Bangladesh, Action Research for Community Adaptation in Bangladesh, International Centre for Climate Change and Development, and Bangladesh Centre for Advanced Studies, Dhaka, Bangladesh, 45 pp.

Fazey, I., J.G.P. Gamarra, J. Fischer, M.S. Reed, L.C. Stringer, and M. Christie, 2010: Adaptation strategies for reducing vulnerability to future environmental change. *Frontiers in Ecology and the Environment*, **8(8)**, 414-422.

Feely, R.A., C.L. Sabine, J. Hernandez-Ayon, D. Ianson, and B. Hales, 2008: Evidence for upwelling of corrosive "acidified" water onto the continental shelf. *Science*, **320(5882)**, 1490-1492.

Fergurson, G. and T. Gleeson, 2012: Vulnerability of coastal aquifers to groundwater use and climate change. *Nature Climate Change*, **2**, 342-345.

Fernández, C., 2011: The retreat of large brown seaweeds on the north coast of Spain: the case of *Saccorhiza polyschides*. *European Journal of Phycology*, **46**, 352-360.

Few, R., K. Brown, and E.L. Tompkins, 2007: Climate change and coastal management decisions: insights from Christchurch Bay, UK. *Coastal Management*, **35(2-3)**, 255-270.

Findlay, H.S., M.T. Burrows, M.A. Kendall, J.I. Spicer, and S. Widdicombe, 2010: Can ocean acidification affect population dynamics of the barnacle *Semibalanus balanoides* at its southern range edge? *Ecology*, **91(10)**, 2931-2940.

Folke, C., T. Hahn, P. Olsson, and J. Norberg, 2005: Adaptive governance of social-ecological systems. *Annual Review of Environment and Resources*, **30**, 441-473.

Foufoula-Georgiou, E., J. Syvitski, C. Paola, C.T. Hoanh, P. Tuong, C. Vörösmarty, H. Kremer, E. Brondizio, Y. Saito, and R. Twilley, 2011: International Year of Deltas 2013: a proposal. *Eos, Transactions of American Geophysical Union*, **92**, 340-341.

Frazier, T.G., N. Wood, and B. Yarnal, 2010: Stakeholder perspectives on land-use strategies for adapting to climate-change-enhanced coastal hazards. *Applied Geography*, **30(4)**, 506-517.

Fujii, T. and D. Raffaelli, 2008: Sea-level rise, expected environmental changes and responses of intertidal benthic macrofauna in the Humber estuary, UK. *Marine Ecology Progress Series*, **371**, 23-35.

Galloway, J.N., F.J. Dentener, D.G. Capone, E.W. Boyer, R.W. Howarth, S.P. Seitzinger, G.P. Asner, C.C. Cleveland, P.A. Green, E.A. Holland, D.M. Karl, A.F. Michaels, J.H. Porter, A.R. Townsend, and C.J. Vorosmarty, 2004: Nitrogen cycles: past, present, and future. *Biogeochemistry*, **70(2)**, 153-226.

Ganachaud, A., A.S. Gupta, J. Brown, K. Evans, C. Maes, L. Muir, and F. Graham, 2013: Projected changes in the tropical Pacific Ocean of importance to tuna fisheries, *Climatic Change*, **119(1)**, 163-179.

Gardner, T. A., I.M. Cote, J.A. Gill, A. Grant, and A.R. Watkinson, 2003: Long-term region-wide declines in Caribbean corals. *Science*, **301(5635)**, 958-960.

Garrabou, J., R. Coma, N. Bensoussan, M. Bally, P. Chevaldonné, M. Cigliano, D. Diaz, J.G. Harmelin, M.C. Gambi, D.K. Kersting, J.B. Ledoux, C. Lejeusne, C. Linares, C. Marschal, T. Pérez, M. Ribes, J.C. Romano, E. Serrano, N. Teixido, O. Torrents, M. Zabala, F. Zuberer, and C. Cerrano, 2009: Mass mortality in Northwestern Mediterranean rocky benthic communities: effects of the 2003 heat wave. *Global Change Biology*, **15**, 1090-1103.

GBRMPA (Great Barrier Reef Marine Park Authority), 2012: *Great Barrier Reef Climate Change Adaptation Strategy and Action Plan 2012-2017*. Great Barrier Reef Marine Park Authority (GBRMPA), Townsville, QLD, Australia, 23 pp.

Gedney, N., P.M. Cox, R.A. Betts, O. Boucher, C. Huntingford, and P.A. Stott, 2006: Detection of a direct carbon dioxide effect in continental river runoff records. *Nature*, **439(7078)**, 835-838.

Geospatial Information Authority of Japan, 2011: Crustal movements in the Tohoku District. In: *Report of the Coordinating Committee for Earthquake Prediction (CCEP), Vol. 86*. pp. 184-272 (in Japanese).

Gero, A., K. Meheux, and D. Dominey-Howes, 2011: Integrating community based disaster risk reduction and climate change adaptation: examples from the Pacific. *Natural Hazards and Earth System Sciences*, **11,** 101-113.

Gilbert, D., N.N. Rabalais, R.J. D'az, J. Zhang, 2010: Evidence for greater oxygen decline rates in the coastal ocean than in the open ocean. *Biogeosciences*, **7(7)**, 2283-2296.

Gilman, E., J.C. Ellison, V. Jungblut, H. Van Lavieren, L. Wilson, F. Areki, G. Brighouse, J. Bungitak, E. Dus, M. Henry, M. Kilman, E. Matthews, I. Sauni Jr., N. Teariki-Ruatu, S. Tukia, and K. Yuknavage, 2006: Adapting to Pacific Island mangrove responses to sea level rise and climate change. *Climate Research*, **32(3)**, 161-176.

Giridharan, R., S.S.Y. Lau, S. Ganesan, and B. Givoni, 2007: Urban design factors influencing heat island intensity in high-rise high-density environments of Hong Kong. *Building and Environment*, **42(10)**, 3669-3684.

Gomez, N., J.X. Mitrovica, P. Huybers, and P.U. Clark, 2010: Sea level as a stabilizing factor for marine-ice-sheet grounding lines. *Nature Geosciences*, **3(12)**, 850-853.

González-Riancho, P., M. Sano, R. Medina, O. Garcia-Aguilar, and J. Areizaga, 2009: A contribution to the implementation of ICZM in the Mediterranean developing countries. *Ocean and Coastal Management*, **52**, 545-558.

Gornitz, V., 1991: Global coastal hazards from future sea level rise. *Global and Planetary Change*, **3(4)**, 379-398.

Grantham, B.A., F. Chan, K.J. Nielsen, D.S. Fox, J.A. Barth, A. Huyer, J. Lubchenco, and B.A. Menge, 2004: Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific. *Nature*, **429(6993)**, 749-754.

Greenstein, B.J. and J.M. Pandolfi, 2008: Escaping the heat: range shifts of reef coral taxa in coastal Western Australia. *Global Change Biology*, **14(3)**, 513-528.

Greiner, J.T., K.J. McGlathery, J. Gunnell, and B.A. McKee, 2013: Seagrass restoration enhances "blue carbon" sequestration in coastal waters. *PLoS ONE*, **8(8)**, e72469, doi:10.1371/journal.pone.0072469.

Grieneisen, M.L. and M. Zhang, 2011: The current status of climate change research. *Nature Climate Change*, **1(2)**, 72-73.

Gutierrez, B.T., N.G. Plant, and E.R. Thieler, 2011: A Bayesian network to predict coastal vulnerability to sea-level rise. *Journal of Geophysical Research*, **116**, F02009, doi: 10.1029/2010JF001891.

Haasnoot, M., J.H. Kwakkel, W.E. Walker, and J. ter Maat, 2013: Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, **23(2)**, 485-498.

Hadley, D., 2009: Land use and the coastal zone. *Land Use Policy*, **265**, S198-S203.

Hadwen, W.L., S.J. Capon, E. Poloczanska, W. Rochester, T. Martin, L. Bay, M. Pratchett, J. Green, B. Cook, A. Berry, A. Lolonde, and S. Fahey, 2011: *Climate Change Responses and Adaptation Pathways in Australian Coastal Ecosystems: Synthesis Report.* Report for the National Climate Change Adaptation Research Facility, Gold Coast, Australia, 359 pp.

Hagedorn, K., K. Artz, and U. Peters, 2002: Institutional arrangements for environmental co-operatives: a conceptual framework. In: *Environmental Cooperation and Institutional Change: Theories and Policies for European Agriculture* [Hagedorn, K. (ed.)]. New Horizons in Environmental Economics Series [Oates, W. and H. Folmer (Series eds.)]. Edward Elgar Publishing, Cheltenham, UK and Northampton, MA, USA, pp. 3-25.

Haigh, I., R. Nicholls, and N. Wells, 2010: Assessing changes in extreme sea levels: application to the English Channel, 1900-2006. *Continental Shelf Research*, **30(9)**, 1042-1055.

Hallegatte, S., 2009: Strategies to adapt to an uncertain climate change. *Global Environmental Change: Human and Policy Dimensions*, **19(2)**, 240-247.

Hallegatte, S., C. Green, R.J. Nicholls, and J. Corfee-Morlot, 2013: Future flood losses in major coastal cities. *Nature Climate Change*, **3**, 802-806.

Hallegraeff, G.M., 2010: Ocean climate change, phytoplankton community responses and harmful algal blooms: a formidable predictive challenge. *Journal of Phycology*, **46(2)**, 220-235.

Haller, I., N. Stybel, S. Schumacher, and M. Mossbauer, 2011: Will beaches be enough? Future changes for coastal tourism at the German Baltic Sea. *Journal of Coastal Research*, **SI 61**, 70-80.

Halpern, B.S., S. Walbridge, K.A. Selkoe, C.V. Kappel, F. Micheli, C. D'Agrosa, J.F. Bruno, K.S. Casey, C. Ebert, H.E. Fox, R. Fujita, D. Heinemann, H.S. Lenihan, E. Madin, M.T. Perry, E.R. Selig, M. Spalding, R. Steneck, and R. Watson, 2008: A global map of human impact on marine ecosystems. *Science*, **319(5865)**, 948-952.

Hanak, E. and G. Moreno, 2012: California coastal management with a changing climate. *Climatic Change*, **111**, 45-73.

Handmer, J., Y. Honda, Z.W. Kundzewicz, N. Arnell, G. Benito, J. Hatfield, I.F. Mohamed, P. Peduzzi, S. Wu, B. Sherstyukov, K. Takahashi, and Z. Yan, 2012: Changes in impacts of climate extremes: human systems and ecosystems. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 231-290.

Hanson, S. and R.J. Nicholls, 2012: Extreme flood events and port cities through the twenty-first century. In: *Maritime Transport and the Climate Change Challenge* [Asariotis, R. and H. Benemara (eds)]. Earthscan/Routledge, New York, NY, USA, 243 pp.

Hanson, S., R. Nicholls, N. Ranger, S. Hallegatte, J. Dorfee-Morlot, C. Herweijer, and J. Chateau, 2011: A global ranking of port cities with high exposure to climate extremes. *Climatic Change*, **104(1)**, 89-111.

Hapke, C., E. Himmelstoss, M. Kratzmann, J. List, and E.R. Thierler, 2011: *National Assessment of Shoreline: Historical Shoreline Changes along the New England and Mid-Atlantic Coasts.* United States Geological Survey (USGS) Open-File Report 2010-1118, USGS, Reston, VA, USA, 57 pp.

Haq, M.Z., M. Robbani, M. Ali, Mainul Hasan, Mahmudul Hasan, J. Uddin, M. Begum, J. Teixeira da Silva, X.-Y. Pan, and R. Karim, 2012: Damage and management of cyclone Sidr-affected homestead tree plantations: a case study from Patuakhali, Bangladesh. *Natural Hazards*, **64(2)**, 1305-1322.

Hare, J.A., M.A. Alexander, M.J. Fogarty, E.H. Williams, and J.D. Scott, 2010: Forecasting the dynamics of a coastal fishery species using a coupled climate-population model. *Ecological Applications*, **20**, 452-464.

Hares, A., J. Dickinson, and K. Wilkes, 2009: Climate change and the air travel decisions of UK tourists. *Journal of Transport Geography*, **18**, 466-473.

Harley, C.D.G., 2008: Tidal dynamics, topographic orientation, and temperature-mediated mass mortalities on rocky shores. *Marine Ecology Progress Series*, **371**, 37-46.

Harley, C.D.G., 2011: Climate change, keystone predation, and biodiversity loss. *Science*, **334(6059)**, 1124-1127.

Harley, M.D., I.L. Turner, A.D. Short, and R. Ranasinghe, 2010: Interannual variability and controls of the Sydney wave climate. *International Journal of Climatology*, **30**, 1322-1335.

Harper, B., T. Hardy, L. Mason, and R. Fryar, 2009: Developments in storm tide modelling and risk assessment in the Australian region, *Natural Hazards*, **51(1)**, 225-238.

Hashizume, M., B. Armstrong, S. Hajat, Y. Wagatsuma, A.S.G. Faruque, T. Hayashi, and D.A. Sack, 2007: Association between climate variability and hospital visits for non-cholera diarrhoea in Bangladesh: effects and vulnerable groups. *International Journal of Epidemiology*, **36**, 1030-1037.

Haslett, S.K., 2009: *Coastal Systems*. 2nd edn., Routledge, Abingdon, UK, 216 pp.

Hawkins, S.J., P.J. Moore, M.T. Burrows, E. Poloczanska, N. Mieszkowska, R. Herbert, S.R. Jenkins, R.C. Thompson, M.J. Genner, and A.J. Southward, 2008: Complex interactions in a rapidly changing world: responses of rocky shore communities to recent climate change. *Climate Research*, **37(2-3)**, 123-133.

Hay, J., 2012: *Disaster Risk Reduction and Climate Change Adaptation in the Pacific: An Institutional and Policy Analysis*. United Nations Development Programme (UNDP) and United Nations Office for Disaster Risk Reduction (UNISDR), Suva, Fiji, 76 pp.

Headland, J.R., D. Trivedi, and R.H. Boudreau, 2011: Coastal structures and sea level rise: adaptive management approach. In: *Coastal Engineering Practice* [Magoon, O.T., R.M. Nobel, D.D. Treadwell, and Y.C. Kim (eds.)]. Proceedings of the 2011 Conference on Coastal Engineering Practice, held in San Diego, California, August 21-24, 2011, American Society of Civil Engineers, Reston, VA, USA, pp. 449-459.

Helmuth, B., C. Harley, P.M. Halpin, D. Oandapos M, G.E. Hofmann, and C.A. Blanchette, 2002: Climate change and latitudinal patterns of intertidal thermal stress. *Science*, **298(5595)**, 1015-1017.

Helmuth, B., N. Mieszkowska, P. Moore, and S.J. Hawkins, 2006: Living on the edge of two changing worlds: forecasting the responses of rocky intertidal ecosystems to climate change. *Annual Review of Ecology Evolution and Systematics*, **37**, 373-404.

Hemer, M.A., Y. Fan, N. Mori, A. Semedo, and X.L. Wang, 2013: Projected changes in wave climate from a multi-model ensemble. *Nature Climate Change*, **3**, 471-476.

Hemminga, M.A. and C.M. Duarte 2000: *Seagrass Ecology*. Cambridge University Press, Cambridge, UK and New York, NY, USA, 298 pp.

Hendriks, I.E., C.M. Duarte, and M. Álvarez, 2010: Vulnerability of marine biodiversity to ocean acidification: a meta-analysis. *Estuarine, Coastal and Shelf Estuarine Science*, **86**, 157-164.

Hiddink, J.G. and R. Hofstede, 2008: Climate induced increases in species richness of marine fishes. *Global Change Biology*, **14**, 453-460.

Hinkel, J., 2011: "Indicators of vulnerability and adaptive capacity": towards a clarification of the science policy interface. *Global Environmental Change*, **21**, 198-208.

Hinkel, J. and R.J.T. Klein, 2009: The DINAS-COAST project: Developing a tool for the dynamic and interactive assessment of coastal vulnerability. *Global Environmental Change*, **19(3)**, 384-395.

Hinkel, J., S. Bisaro, T. Downing, M.E. Hofmann, K. Lonsdale, D. Mcevoy, and J.D. Tabara, 2010: Learning to adapt: re-framing climate change adaptation. In: *Making Climate Change Work for Us: European Perspectives on Adaptation and Mitigation Strategies* [Hulme, M. and H. Neufeldt (ed.)]. Cambridge University Press, Cambridge, UK, pp. 113-134.

Hinkel, J., S. Brown, L. Exner, R.J. Nicholls, A.T. Vafeidis, and A.S. Kebede, 2011: Sea-level rise impacts on Africa and the effects of mitigation and adaptation: an application of DIVA. *Regional Environmental Change*, **12**, 207-224.

Hinkel, J., D.P. van Vuuren, R.J. Nicholls, and R.J.T. Klein, 2013: The effects of mitigation and adaptation on coastal impacts in the 21st century. An application of the DIVA and IMAGE models. *Climatic Change*, **117(4)**, 783-794.

Hoegh-Guldberg, O., P.J. Mumby, A.J. Hooten, R.S. Steneck, P. Greenfield, E. Gomez, C.D. Harvell, P.F. Sale, A.J. Edwards, K. Caldeira, N. Knowlton, C.M. Eakin, R. Iglesias-Prieto, N. Muthiga, R.H. Bradbury, A. Dubi, and M.E. Hatziolos, 2007: Coral reefs under rapid climate change and ocean acidification. *Science*, **318(5857)**, 1737-1742.

Hoeke, R.K., K.L. McInnes, J. Kruger, R. McNaught, J. Hunter, and S. Smithers, 2013: Widespread inundation of Pacific islands by distant-source wind-waves. *Global and Planetary Change*, **108**, 128-138.

Hofmann, A.F., J.J. Middelburg, K. Soetaert, and F. Meysman, 2009: pH modelling in aquatic systems with time-variable acid-base dissociation constants applied to the turbid, tidal Scheldt estuary. *Biogeosciences*, **6**, 1539-1561.

Hofmann, G.E., J.E. Smith, K.S Johnson, U. Send, L.A. Levin, F. Micheli, A. Paytan, N.N. Price, B. Peterson, Y. Takeshita, P.G. Matson, E.D. Crook, K.J. Kroeker, M.C. Gambi, E.B. Rivest, C.A. Frieder, P.C. Yu, and T.R. Martz, 2011: High-frequency dynamics of ocean pH: a multi-ecosystem comparison. *PLoS ONE*, **6(12)**, e28983, doi:10.1371/journal.pone.0028983.

Hofstede, J., 2008: Climate change and coastal adaptation strategies: the Schleswig-Holstein perspective. *Baltica*, **21(1-2)**, 71-78.

Holling, C.S., 1978: *Adaptive Environmental Assessment and Management.* A Wiley – Interscience Publication, The Wiley IIASA International Series on Applied Systems Analysis, Vol. 3, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, and John Wiley and Sons, Chichester, UK and New York, NY, USA, 377 pp.

Hong, B. and J. Shen, 2012: Responses of estuarine salinity and transport processes to potential future sea-level rise in the Chesapeake Bay. *Estuarine, Coastal and Shelf Science*, **104-105**, 33-45.

Hopkins, T.S., D. Bailly, R. Elmgren, G. Glegg, A. Sandberg, and J.G. Stottrup, 2012: A systems approach framework for the transition to sustainable development: potential value based on coastal experiments. *Ecology and Society*, **17(3)**, 39, doi:10.5751/ES-05266-170339.

Horton, R., C. Rosenzweig, V. Gornitz, D. Bader, and M. O'Grady, 2010: Climate risk information: climate change scenarios and implications for NYC infrastructure. New York City Panel on Climate Change. *Annals of the New York Academy of Sciences*, **1196 (1)**, 147-228.

Howarth, R., F. Chan, D.J. Conley, J. Garnier, S.C. Doney, R. Marino, and G. Billen, 2011: Coupled biogeochemical cycles: eutrophication and hypoxia in temperate estuaries and coastal marine ecosystems. *Frontiers in Ecology and the Environment*, **9(1)**, 18-26.

Hunt, A. and P. Watkiss, 2011: Climate change impacts and adaptation in cities: a review of the literature. *Climatic Change*, **104(1)**, 13-49.

Hunter, J., 2012: A simple technique for estimating an allowance for uncertain sea-level rise. *Climatic Change*, **113(2)**, 239-252.

Hunter, J.R., J.A. Church, N.J. White, and X. Zhang, 2013: Towards a global regionally varying allowance for sea-level rise. *Ocean Engineering*, **71(1)**,17-27.

Huq, S. and H. Reid, 2007: *Community Based Adaptation: A Vital Approach to the Threat Climate Change Poses to the Poor*. International Institute for Environment and Development (IIED) Briefing Paper, London, UK, 2 pp.

Ibrahim, H.S. and D. Shaw, 2012: Assessing progress toward integrated coastal zone management: some lessons from Egypt. *Ocean and Coastal Management*, **58**, 26-35.

IPCC, 2000: *Emissions Scenarios.* A *Special Report of Working Group III of the Intergovernmental Panel on Climate Change* [Nakićenović, N. and R. Swart (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 570 pp.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. *A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 594 pp.

Irish, J.L, A.E. Frey, J.D. Rosati, F. Olivera, L.M. Dunkin, J.M. Kaihatu, C.M. Ferreira, and B.L. Edge, 2010: Potential implications of global warming and barrier island degradation on future hurricane inundation, property damages, and population impacted. *Ocean and Coastal Management*, **53**, 645-657.

Isager, L., 2008: *Coastal Zone Management in Developing Countries with Kenya as a Particular Example*. Geocenter Denmark, Copenhagen, Denmark, 52 pp.

IUCN, 2008: *Ecosystem-based Adaptation: An Approach for Building Resilience and Reducing Risk for Local Communities and Ecosystems.* A submission by International Union for Conservation of Nature (IUCN) to the Chair of the AWG-LCA with respect to the Shared Vision and Enhanced Action on Adaptation, on behalf of: IUCN, The Nature Conservancy, WWF, Conservation International, BirdLife International, Indigenous Peoples of Africa Co-ordinating Committee, Practical Action, WILD Foundation, Wildlife Conservation Society, Fauna and Flora International and Wetlands International, IUCN, Gland, Switzerland, 2 pp.

Jackson, A.C. and J. MacIlvenny, 2011: Coastal squeeze on rocky shores in northern Scotland and some possible ecological impacts. *Journal of Experimental Marine Biology and Ecology*, **400**, 314-321.

Jacob, K.H., V. Gornitz, and C. Rosenzweig, 2007: Vulnerability of the New York City metropolitan area to coastal hazards, including sea-level rise: inferences for urban coastal risk management and adaptation policies. In: *Managing Coastal Vulnerability* [McFadden, L., R.J. Nicholls, and E. Penning-Roswell (eds.)]. Elsevier, Amsterdam, Netherlands and Boston, MA, USA, pp. 141-158.

Jaykus, L.-A., M. Woolridge, J.M. Frank, M. Miraglia, A. McQuatters-Gollop, C. Tirado, R. Clarke, and M. Friel, 2008: *Climate Change: Implications for Food Safety*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 49 pp.

Jentoft, S., 2007: Limits of governability: institutional implications for fisheries and coastal governance. *Marine Policy*, **31**, 360-370.

Jentoft, S., 2009: Future challenges in environmental policy relative to integrated coastal zone management. In: *Integrated Coastal Zone Management* [Moksness, E., E. Dahl, and J. Støttrup (eds.)]. Wiley-Blackwell, Chichester, UK, pp. 157-169.

Jeppesen, E., M. Sondergaard, A.R. Pedersen, K. Jurgens, A. Strzelczak, T.L. Lauridsen, and L.S. Johansson, 2007: Salinity induced regime shift in shallow brackish lagoons. *Ecosystems*, **10**, 47-57.

Jimenez, J.A., P. Ciavola, Y. Balouin, C. Armaroli, E. Bosom, and M. Gervais, 2009: Geomorphic coastal vulnerability to storms in microtidal fetch-limited environments: application to NW Mediterranean and N Adriatic Seas. *Journal of Coastal Research*, **2(56)**, 1641-1645.

Johnson, C.R., S.C. Banks, N.S. Barrett, F. Cazassus, P.K. Dunstan, G.J. Edgar, S.D. Frusher, C. Gardner, M. Haddon, F. Helidoniotis, K.L. Hill, N.J. Holbrook, G.W. Hosie, P.R. Last, S.D. Ling, J. Melbourne-Thomas, K. Miller, G.T. Pecl, A.J. Richardson, K.R Ridgway, S.R. Rintoul, D.A. Ritz, D.J. Ross, J.C. Sanderson, S.A. Shepherd, A. Slotwinski, K.M. Swadling, and N. Taw, 2011: Climate change cascades: shifts in oceanography, species' ranges and subtidal marine community dynamics in eastern Tasmania. *Journal of Experimental Marine Biology and Ecology*, **400(1-2)**, 17-32.

Jones, H.P., D.G. Hole, and E.S. Zavaleta, 2012: Harnessing nature to help people adapt to climate change. *Nature Climate Change*, **2**, 504-509.

Jongman, B., P.J. Ward, and J.C.J.H. Aerts, 2012: Global exposure to river and coastal flooding: long term trends and changes. *Global Environmental Change: Human and Policy Dimensions*, **22(4)**, 823-835.

Jordà, G., N. Marbà, and C.M. Duarte, 2012: Mediterranean seagrass vulnerable to regional climate warming. *Nature Climate Change*, **2**, 821-824.

Kabat, P., L.O. Fresco, M.J.C. Stive, C.P. Veerman, J.S.L.J. van Alphen, B.W.A.H. Parmet, W. Hazeleger, and C.A. Katsman, 2009: Dutch coasts in transition. *Nature Geoscience*, **2**, 450-452.

Kates, R.W., 2000: Cautionary tales: adaptation and the global poor. *Climatic Change*, **45(1)**, 5-17.

Katsman, C.A., J.J. Beersma, H.W. van den Brink, J.A. Church, W. Hazeleger, R.E. Kopp, D. Kroon, J. Kwadijk, R. Lammersen, J. Lowe, M. Oppenheimer, H.P. Plag, J. Ridley, H. von Storch, D.G. Vaughan, P. Vellinga, L.L.A. Vermeersen, R.S.W. van de Wal, and R. Weisse, 2011: Exploring high-end scenarios for local sea level rise to develop flood protection strategies for a low-lying delta – the Netherlands as an example. *Climate Change*, **109**, 617-645.

Kay, R.C., 2012: Adaptation by ribbon cutting: time to understand where the scissors are kept. *Climate and Development*, **4(2)**, 75-77.

Kay, R. and J. Adler, 2005: *Coastal Planning and Management*. 2nd edn., CRC Press, London, UK, 400 pp.

Kebede, A.S. and R.J. Nicholls, 2012: Exposure and vulnerability to climate extremes: population and asset exposure to coastal flooding in Dar es Salaam, Tanzania. *Regional Environmental Change*, **12**, 81-94.

Kennedy, H. and M. Björk, 2009: Seagrass meadows. In: *The Management of Natural Coastal Carbon Sinks* [Laffoley, D. and G. Grimsditch (eds.)]. International Union for Conservation of Nature (IUCN), Gland, Switzerland, pp. 23-29.

Kenter, J.O., T. Hyde, M. Christie, and I. Fazey, 2011: The importance of deliberation in valuing ecosystem services in developing countries – evidence from the Solomon Islands. *Global Environmental Change: Human and Policy Dimensions*, **21(2)**, 505-521.

Kettle, N.P., 2012: Exposing compounding uncertainties in sea level rise assessments. *Journal of Coastal Research*, **28**, 161-173.

Khan, A., S.K. Mojumder, S. Kovats, and P. Vineis, 2008: Saline contamination of drinking water in Bangladesh. *The Lancet*, **371(9610)**, 385.

Khan, A.S., A. Ramachandran, N. Usha, S. Punitha, and V. Selvam, 2012: Predicted impact of the sea-level rise at Vellar–Coleroon estuarine region of Tamil Nadu coast in India: mainstreaming adaptation as a coastal zone management option. *Ocean and Coastal Management*, **69**, 327-339.

Kiessling, W., C. Simpson, B. Beck, H. Mewis, and J.M. Pandolfi, 2012: Equatorial decline of reef corals during the last Pleistocene interglacial. *Proceedings of the National Academy of Sciences of the United States of America*, **109(52)**, 21378-21383.

Kiker, G.A., R. Muñoz-Carpena, N. Ranger, M. Kiker, and I. Linkov, 2010: Adaptation in coastal systems. In: *Climate: Global Change and Local Adaptation* [Linkov, I. and T.S. Bridges, (eds.)]. Springer, Dordrecht, Netherlands, pp. 375-400.

Kirshen, P., S. Merrill, P. Slovinsky, and N. Richardson, 2012: Simplified method for scenario-based risk assessment adaptation planning in the coastal zone. *Climatic Change*, **113(3-4)**, 919-931.

Kirwan, M.L. and S.M. Mudd, 2012: Response of salt-marsh carbon accumulation to climate change. *Nature*, **489**, 550-553.

Kirwan, M.L., G.R. Guntenspergen, A. D'Alpaos, J.T. Morris, S.M. Mudd, and S. Temmerman, 2010: Limits on the adaptability of coastal marshes to rising sea level. *Geophysical Research Letters*, **37(23)**, L23401, doi:10.1029/2010GL045489.

Klein, R.J.T., S. Huq, F. Denton, T.E. Downing, R.G. Richels, J.B. Robinson, and F.L. Toth, 2007: Inter- relationships between adaptation and mitigation. In: *Climate Change 2007: Impacts and Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 745-777.

Kleiner, K., 2011: Data on demand. *Nature Climate Change*, **1(1)**, 10-12.

Kleypas, J.A., G. Danabasoglu, and J.M. Lough, 2008: Potential role of the ocean thermostat in determining regional differences in coral reef bleaching events. *Geophysical Research Letters*, **35(3)**, L03613, doi:10.1029/2007GL032257.

Kleypas, J.A., K.R.N. Anthony, and J.-P.Gattuso, 2011: Coral reefs modify their seawater carbon chemistry: case study from a barrier reef (Moorea, French Polynesia). *Global Change Biology*, **17**, 3667-3678.

Koelle, K., X. Rodo, M. Pascual, M. Yunus, and G. Mostafa, 2005: Refractory periods and climate forcing in cholera dynamics. *Nature*, **436(7051)**, 696-700.

Kolivras, K.N., 2010: Changes in dengue risk potential in Hawaii, USA, due to climate variability and change. *Climate Research*, **42**, 1-11.

Kolker, A.S., M.A. Allison, and S. Hameed, 2011: An evaluation of subsidence rates and sea-level variability in the northern Gulf of Mexico. *Geophysical Research Letters*, **38(21)**, L21404, doi:10.1029/2011GL049458.

Kolstad, E.W. and K.A. Johansson, 2011: Uncertainties associated with quantifying climate change impacts on human health: a case study for diarrhea. *Environmental Health Perspectives*, **119**, 299-305.

Kriegler, E., B.C. O'Neill, S. Hallegatte, T. Kram, R.J. Lempert, R.H. Moss, and T. Wilbanks, 2012: The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathways. *Global Environmental Change: Human and Policy Dimensions*, **22(4)**, 807-822.

Kroeker, K.J., F. Michell, M.C. Gambi, and T.R. Martz, 2011: Divergent ecosystem responses within a benthic marine community to ocean acidification. *Proceedings of the National Academy of Sciences of the United States of America*, **108**, 14515-14520.

Kroeker, K.J., R.C. Kordas Ryan, I. Hendriks, L. Ramajo, G. Singh, C. Duarte, and J. Gattuso, 2013: Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. *Global Change Biology*, **19(6)**, 1884-1896.

Kroeze, C., E. Dumont, and S. Seitzinger, 2010: Future trends in emissions of N_2O from rivers and estuaries. *Journal of Integrative Environmental Sciences*, **SI 7**, 71-78.

Kwadijk, J.C.J., M. Haasnoot, J.P.M. Mulder, M.M.C. Hoogvliet, A.B.M. Jeuken, R.A.A. van der Krogt, N.G.C. van Oostrom, H.A. Schelfhout, E.H. van Velzen, H. van Waveren, and M.J.M. de Wit, 2010: Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands. *Wiley Interdisciplinary Reviews: Climate Change*, **1(5)**, 729-740.

Langley, J.A., K.L. McKee, D.R. Cahoon, J.A. Cherry, and J.P. Megonigal, 2009: Elevated CO_2 stimulates marsh elevation gain, counterbalancing sea-level rise. *Proceedings of the National Academy of Sciences of the United States of America*, **106(15)**, 6182-6186.

Langton, M., M. Parsons, S. Leonard, K. Auty, D. Bell, P. Burgess, S. Edwards, R. Howitt, S. Jackson, V. McGrath, and J. Morrison, 2012: *National Climate Change Adaptation Research Plan for Indigenous Communities*. National Climate Change Adaptation Research Facility (NCCARF), Gold Coast, Australia, 48 pp.

Larsen, P.H., S. Goldsmith, O. Smith, M.L. Wilson, K. Strzepek, P. Chinowsky, and B. Saylor, 2008: Estimating future costs for Alaska public infrastructure at risk from climate change. *Global Environment Change*, **18**, 442-457.

Lasalle, G. and E. Rochard, 2009: Impact of twenty-first century climate change on diadromous fish spread over Europe, North Africa and the Middle East. *Global Change Biology*, **15**, 1072-1089.

Last, P.R., W.T. White, D.C. Gledhill, A.J. Hobday, R. Brown, G.J. Edgar, and G. Pecl, 2011: Long-term shifts in abundance and distribution of a temperate fish fauna: a response to climate change and fishing practices. *Global Ecology and Biogeography*, **20**, 58-72.

Lata, S. and P. Nunn, 2012: Misperceptions of climate-change risk as barriers to climate-change adaptation: a case study from the Rewa Delta, Fiji. *Climatic Change*, **110(1-2)**, 169-186.

Leatherman, S., K. Zhang, and B. Douglas, 2000a: Sea level rise shown to drive coastal erosion. *EOS Transactions of the American Geophysical Union*, **81(6)**, 55-57.

Leatherman, S., K. Zhang, and B. Douglas, 2000b: Sea level rise shown to drive coastal erosion: a reply. *EOS Transactions of the American Geophysical Union*, **81(38)**, 437-441.

Ledoux, L., S. Cornell, T. O'Riordan, R. Harvey, and L. Banyard, 2005: Towards sustainable flood and coastal management: identifying drivers of, and obstacles to, managed realignment. *Land Use Policy*, **22(2)**,129-144.

Lehner, B., C.R. Liermann, C. Revenga, C. Vorosmarty, B. Fekete, P. Crouzet, P. Doll, M. Endejan, K. Frenken, J. Magome, C. Nilsson, J.C. Robertson, R. Rodel, N. Sindorf, and D. Wisser, 2011: High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Frontiers in Ecology and the Environment*, **9**, 494-502.

Lemos, M.C., C.J. Kirchhoff, and V. Ramprasad, 2012: Narrowing the climate information usability gap. *Nature Climate Change*, **2**, 789-794.

Lempert, R.J. and M.T. Collins, 2007: Managing the risk of uncertain threshold responses: comparison of robust, optimum, and precautionary approaches. *Risk Analysis*, **27(4)**, 1009-1026.

Lempert, R.J. and M.E. Schlesinger, 2000: Robust strategies for abating climate change. An editorial essay. *Climatic Change*, **45(3-4)**, 387-401.

Lempert, R.J. and M.E. Schlesinger, 2001: Climate-change strategy needs to be robust. *Nature*, **412(6845)**, 375.

Lempert, R.J., R.L. Sriver, and K. Keller, 2012: *Characterizing Uncertain Sea Level Rise Projections to Support Investment Decisions*. White Paper, California Energy Commission's California Climate Change Center, RAND, Santa Monica, CA, USA, 44 pp.

Lerman, A., M. Guidry, A.J. Andersson, and F.T. Mackenzie, 2011: Coastal ocean last glacial maximum to 2100 CO_2-carbonic acid-carbonate system: a modeling approach. *Aquatic Geochemistry*, **17**, 749-773.

Levermann, A., P.U. Clark, B. Marzeion, G.A. Milne, D. Pollard, V. Radic, and A. Robinson, 2013: The multimillennial sea-level commitment of global warming. *Proceedings of the National Academy of Sciences of the United States of America*, **110(34)**, 13745-13750.

Levinton, J., M. Doall, D. Ralston, A. Starke, and B. Allam, 2011: Climate change, precipitation and impacts on an estuarine refuge from disease. *PLoS One*, **6(4)**, e18849, doi:10.1371/journal.pone.0018849.

Lewis, M., K. Horsburgh, P. Bates, and R. Smith, 2011: Quantifying the uncertainty in future coastal flood risk estimates for the UK. *Journal of Coastal Research*, **27(5)**, 870-881.

Li, J., M.H. Wang, and Y.S. Ho, 2011: Trends in research on global climate change: a science citation index expanded-based analysis. *Global and Planetary Change*, **77**, 13-20.

Li, K. and G.S. Li, 2011: Vulnerability assessment of storm surges in the coastal area of Guangdong Province. *Natural Hazards and Earth System Sciences*, **11(7)**, 2003-2010.

Lichter, M., A.T. Vafeidis, R.J. Nicholls, and G. Kaiser, 2011: Exploring data-related uncertainties in analyses of land area and population in the "Low-Elevation Coastal Zone" (LECZ). *Journal of Coastal Research*, **27(4)**, 757-768.

Lima, F.P. and D.S. Wethey, 2012: Three decades of high-resolution coastal sea surface temperatures reveal more than warming. *Nature Communications*, **3**, 704, doi:10.1038/ncomms1713.

Lin, N., K. Emanuel, M. Oppenheimer, and E. Vanmarcke, 2012: Physically based assessment of hurricane surge threat under climate change. *Nature Climate Change*, **2(6)**, 462-467.

Linham, M.M. and R.J. Nicholls, 2010: *Technologies for Climate Change Adaptation: Coastal Erosion and Flooding.* UNEP Risø Centre on Energy, Climate and Sustainable Development, Roskilde, Denmark, 150 pp.

Linham, M.M. and R.J. Nicholls, 2012: Adaptation technologies for coastal erosion and flooding: a review. *Proceedings of the Institute of Civil Engineers – Maritime Engineering*, **165**, 95-111.

Logan, C.A., J.P. Dunne, C.M. Eakin, and S.D. Donner, 2014: Incorporating adaptation and acclimatization into future projections of coral bleaching. *Global Change Biology*, **20**, 125-139.

Lonsdale, K.G., M.J. Gawith, K. Johnstone, R.B. Street, C.C. West, and A.D. Brown, 2010: *Attributes of Well-Adapting Organisations.* Report prepared by the UK Climate Impacts Programme for the Adaptation Sub-Committee, UK Climate Impacts Programme, Oxford, UK, 89 pp.

Losada, I.J, B.G. Reguero, F.J. Mendez, S. Castanedo, A.J. Abascal, and R. Minguez, 2013: Long-term changes in sea-level components in Latin America and the Caribbean. *Global and Planetary Change*, **104**, 34-50.

Lotze, H. K., H.S. Lenihan, B.J. Bourque, R.H. Bradbury, R.G. Cooke, M.C. Kay, S.M. Kidwell, M.X. Kirby, C.H. Peterson, and J.B.C. Jackson, 2006: Depletion, degradation, and recovery potential of estuaries and coastal seas. *Science*, **312**, 1806-1809.

Lowe, J.A., T.P. Howard, A. Pardaens, J. Tinker, J. Holt, S. Wakelin, G. Milne, J. Leake, J. Wolf, K. Horsburgh, T. Reeder, G. Jenkins, J. Ridley, S. Dye, and S. Bradley, 2009: *UK Climate Projections Science Report: Marine and Coastal Projections*. Met Office Hadley Centre, Exeter, UK, 95 pp.

Mangal, T.D., S. Paterson, and A. Fenton, 2008: Predicting the impact of long-term temperature changes on the epidemiology and control of *Schistosomiasis*: a mechanistic model. *PLoS ONE*, **3(1),** e1438, doi:10.1371/journal.pone.0001438.

Manzello, D.P., 2010: Coral growth with thermal stress and ocean acidification: lessons from the eastern tropical Pacific. *Coral Reefs*, **29(3)**, 749-758.

Manzello, D.P., J.A. Kleypas, D.A. Budd, C.M. Eakin, P.W. Glynn, and C. Langdon, 2008: Poorly cemented coral reefs of the eastern tropical Pacific: possible insights into reef development in a high-CO_2 world. *Proceedings of the National Academy of Sciences of the United States of America*, **105(30)**, 10450-10455.

Marbà, N. and C.M. Duarte, 2010: Mediterranean warming triggers seagrass (*Posidonia oceanica*) shoot mortality. *Global Change Biology*, **16**, 2366-2375.

Marchand, M., A. Sanchez-Arcilla, M. Ferreira, J. Gault, J.A. Jiménez, M. Markovic, J. Mulder, L. van Rijn, A. Stănică, W. Sulisz, and J. Sutherland, 2011: Concepts and science for coastal erosion management – an introduction to the Conscience framework. *Ocean and Coastal Management*, **54(12)**, 859-866.

Marcos, M., M.N. Tsimplis, and A.G.P. Shaw, 2009: Sea level extremes in southern Europe. *Journal of Geophysical Research: Oceans*, **114(C1)**, C01007, doi:10.1029/2008JC004912.

Marriner, N., C. Flaux, C. Morhange, and D. Kaniewski, 2012: Nile Delta's sinking past: quantifiable links with Holocene compaction and climate-driven changes in sediment supply? *Geology*, **40(12)**, 1083-1086.

Martinez, G., L. Bizikova, D. Blobel, and R. Swart, 2011: Emerging climate change coastal adaptation strategies and case studies around the world. In: *Global Change and Baltic Coastal Zones Coastal Research Library*, *Vol. 1* [Schernewski, G., J. Hofstede, and T. Neumann (eds.)]. Springer-Verlag, Berlin and Heidelberg, Germany, pp. 249-273.

Mazzotti, S., A. Lambert, M. Van der Kooij, and A. Mainville, 2009: Impact of anthropogenic subsidence on relative sea-level rise in the Fraser River delta. *Geology*, **37**, 771-774.

McEvoy, D. and J. Mullett, 2013: *Enhancing the Resilience of Seaports to a Changing Climate: Research Synthesis and Implications for Policy and Practice*. Work Package 4 of Enhancing the Resilience of Seaports to a Changing Climate Report Series, National Climate Change Adaptation Research Facility, Gold Coast, Australia, 49 pp.

McFadden, L., 2008: Exploring the challenges of integrated coastal zone management and reflecting on contributions to 'integration' from geographical thought. *The Geographical Journal*, **174(4)**, 299-314.

McGinnis, M.V. and C.E. McGinnis, 2011: Adapting to climate impacts in California: the importance of civic science in local coastal planning. *Coastal Management*, **39(3)**, 225-241.

McGranahan, G., D. Balk, and B. Anderson, 2007: The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization*, **19**, 17-37.

McInnes, R., 2006: *Responding to the Risks from Climate Change in Coastal Zones: A Good Practice Guide*. Centre for the Coastal Environment, Isle of Wight Council, Newport, Isle of Wight, UK, 88 pp.

McKee, K., K. Rogers, and N. Saintilan, 2012: Response of salt marsh and mangrove wetlands to changes in atmospheric CO_2, climate, and sea level. In: *Global Change and the Function and Distribution of Wetlands* [Middleton, B.A. (ed.)]. Springer, Dordrecht, Netherlands, pp. 63-96.

McLain, R. and R. Lee, 1996: Adaptive management: promises and pitfalls. *Environmental Management*, **20(4)**, 437-448.

McLeod, E., B. Poulter, J. Hinkel, E. Reyes, and R. Salm, 2010: Sea-level rise impact models and environmental conservation: a review of models and their applications. *Ocean and Coastal Management*, **53(9)**, 507-517.

McLeod, E., G.L. Chmura, S. Bouillon, R. Salm, M. Björk, C.M. Duarte, C.E. Lovelock, W.H. Schlesinger, and B.R. Silliman, 2011: A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Frontiers in Ecology and the Environment*, **9(10)**, 552-560.

McNamara, D.E., A.B. Murray, and M.D. Smith, 2011: Coastal sustainability depends on how economic and coastline responses to climate change affect each other. *Geophysical Research Letters*, **38(7)**, L07401, doi:10.1029/2011GL047207.

MEA, 2005: *Ecosystems and Human Well-Being: Synthesis*. Millennium Ecosystem Assessment (MEA), Island Press, Washington, DC, USA, 137 pp.

Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver, and Z.-C. Zhao, 2007: Global climate projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA pp. 747-846.

Meinshausen, M., S.J. Smith, K. Calvin, J.S. Daniel, M.L.T. Kainuma, J. Lamarque, K. Matsumoto, S.A. Montzka, S.C.B. Raper, K. Riahi, A. Thomson, and G.J.M. Velders, 2011: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change*, **109**, 213-241.

Meire, L., K.E.R. Soetaert, and F.J.R. Meysman, 2013: Impact of global change on coastal oxygen dynamics and risk of hypoxia. *Biogeosciences*, **10**, 2633-2653.

Menendez, M. and P.L. Woodworth, 2010: Changes in extreme high water levels based on a quasi-global tide-gauge dataset. *Journal of Geophysical Research: Oceans*, **115**, C10011, doi:10.1029/2009JC005997.

Menge, B.A., F. Chan, and J. Lubchenco, 2008: Response of a rocky intertidal ecosystem engineer and community dominant to climate change. *Ecology Letters*, **11(2)**, 151-162.

Mercer, J., 2010: Disaster risk reduction or climate change adaptation: are we reinventing the wheel? *Journal of International Development*, **22(2)**, 247-264.

Meynecke, J.O. and S. Yip Lee, 2011: Climate-coastal fisheries relationships and their spatial variation in Queensland, Australia. *Fisheries Research*, **110(2)**, 365-376.

Milligan, J., T. O'Riordan, S.A. Nicholson-Cole, and A.R. Watkinson, 2009: Nature conservation for future sustainable shorelines: lessons from seeking to involve the public. *Land Use Policy*, **26**, 203-213.

Milliman, J.D. and K.L. Farnsworth, 2011: *River Discharge to the Coastal Ocean: A Global Synthesis*. Cambridge University Press, Cambridge, UK, 384 pp.

Milne, G.A., W.R. Gehrels, C.W. Hughes, and M.E. Tamisiea, 2009: Identifying the causes of sea-level change. *Nature Geoscience*, **2**, 471-478.

Mimura, N., 2013: Sea-level rise caused by climate change and its implications for society. *Proceedings of the Japan Academy, Series B Physical and Biological Sciences*, **89(7)**, 281-301.

Miranda, P.M.A., J.M.R. Alves, and N. Serra, 2012: Climate change and upwelling: response of Iberian upwelling to atmospheric forcing in a regional climate scenario. *Climate Dynamics*, **40(11-12)**, 2813-2824.

Mitchell, T., M. van Aalst, and P.S. Vllanueva, 2010: *Assessing Progress on Integrating Disaster Risk Reduction and Climate Change Adaptation in Development Processes*. Strengthening Climate Resilience: Discussion Paper 2, Institute of Development Studies, Brighton, UK, 28 pp.

Mondal, P. and A.J. Tatem, 2012: Uncertainties in measuring populations potentially impacted by sea level rise and coastal flooding. *PLoS ONE*, **7(10)**, e48191, doi:10.1371/journal.pone.0048191.

Montaggioni, L.F., 2005: History of Indo-Pacific coral reef systems since the last glaciation: development patterns and controlling factors. *Earth-Science Reviews*, **71(1-2)**, 1-75.

Moreno, A. and B. Amelung, 2009a: How hot is too hot? A survey on climate (change) and tourism. In: *Proceedings of CMT2009, the 6th International Congress on Coastal and Marine Tourism, 23 – 26 June 2009 Port Elizabeth – Nelson Mandela Bay – South Africa* [Albers, A. and P. Myles, (eds.)]. CMT2009/WP/004, Kyle Business Projects, Port Elizabeth, Nelson Mandela Bay, South Africa, pp. 237-241.

Moreno, A. and B. Amelung, 2009b: Climate change and coastal and marine tourism: review and analysis. *Journal of Coastal Research*, **SI 56**, 1140-1144.

Morton, R.A., J.C. Bernier, J.A. Barras, and N.F., Ferina, 2005: *Rapid Subsidence and Historical Wetland Loss in the Mississippi Delta Plain: Likely Causes and Future Implications*. Open File Report 2005-1216, U.S. Department of Interior and U.S. Geological Survey (USGS), 124 pp.

Moser, S.C. and J.A. Ekstrom, 2010: A framework to diagnose barriers to climate change adaptation. *Proceeding of the National Academic of Sciences of the United States of America*, **107(51)**, 22026-22031.

Moser, S.C., R.E. Kasperson, G. Yohe, and J. Agyeman, 2008: Adaptation to climate change in the Northeast United States: opportunities, processes, constraints. *Mitigation and Adaptation Strategies for Global Change*, **13(5-6)**, 643-659.

Moser, S.C., J. Williams, and D.F. Boesch, 2012: Wicked challenges at land's end: managing coastal vulnerability under climate change. *Annual Review of Environment and Resources*, **37**, 51-78.

Moss, R.H., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren, T.R. Carter, S. Emori, M. Kainuma, T. Kram, G.A. Meehl, J.F.B. Mitchell, N. Nakicenovic, K. Riahi, S.J. Smith, R.J. Stouffer, A.M. Thomson, J.P. Weyant, and T.J. Wilbanks, 2010: The next generation of scenarios for climate change research and assessment. *Nature*, **463(7282)**, 747-756.

Mousavi, M., J. Irish, A. Frey, F. Olivera, and B. Edge, 2011: Global warming and hurricanes: the potential impact of hurricane intensification and sea level rise on coastal flooding. *Climatic Change*, **104(3-4)**, 575-597.

Mozumder, P., E. Flugman, and T. Randhir, 2011: Adaptation behavior in the face of global climate change: survey responses from experts and decision makers serving the Florida Keys. *Ocean and Coastal Management*, **54 (1)**, 37-44.

Mudd, S.M., S.M. Howell, and J.T. Morris, 2009: Impact of dynamic feedbacks between sedimentation, sea-level rise, and biomass production on near-surface marsh stratigraphy and carbon accumulation. *Estuarine Coastal and Shelf Sciences*, **82**, 377-389.

Mulder, J.P.M., S. Hommes, and E.M. Horstman, 2011: Implementation of coastal erosion management in the Netherlands. *Ocean and Coastal Management*, **54(12)**, 888-897.

Munroe, R., N. Doswald, D. Roe, H. Reid, A. Giuliani, I. Castelli, and I. Moller, 2011: *Does EbA Work? A Review of the Evidence on the Effectiveness of Ecosystem-Based Approaches to Adaptation.* Policy Brief by the United Nations Environment Programme-World Conservation Monitoring Centre (UNEP-WCMC), BirdLife Inernational, International Institute for Environment and Development (IIED), and the University of Cambridge, ELAN, Cambridge, UK, 4 pp.

Murray, V., G. McBean, M. Bhatt, S. Borsch, T.S. Cheong, W.F. Erian, S. Llosa, F. Nadim, M. Nunez, R. Oyun, and A.G. Suarez, 2012: Case studies. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 487-542.

Myung, H.-N. and J.-Y. Jang, 2011: Causes of death and demographic characteristics of victims of meteorological disasters in Korea from 1990 to 2008. *Environmental Health*, **10**, 82, doi:10.1186/1476-069X-10-82.

Nageswara Rao, K., P. Subraelu, K.Ch.V. Naga Kumar, G. Demudu, B. Hema Malini, A.S. Rajawat, and Ajai, 2010: Impacts of sediment retention by dams on delta shoreline recession: evidences from the Krishna and Godavari deltas, India. *Earth Surface Processes and Landforms*, **35**, 817-827.

Nakashima, D.J., K. Galloway McLean, H.D. Thulstrup, A. Ramos Castillo, and R.T. Rubis, 2012: *Weathering Uncertainty: Traditional Knowledge for Climate Change Assessment and Adaptation*. The United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris, France, and United Nations University (UNU), Darwin, Australia, 120 pp.

Narayan, N., A. Paul, S. Mulitza, and M. Schulz, 2010: Trends in coastal upwelling intensity during the late 20th century. *Ocean Science*, **6(3)**, 815-823.

Narita, D., K. Rehdanz, and R. Tol, 2012: Economic costs of ocean acidification: a look into the impacts on shellfish production. *Climatic Change*, **113(3-4)**, 1049-1063.

Naylor, L.A., W.J. Stephenson, and A.S. Trenhaile, 2010: Rock coast geomorphology: recent advances and future research directions. *Geomorphology*, **114 (1-2)**, pp. 3-11.

Nellemann, C., E. Corcoran, C.M. Duarte, L. Valdes, D. De Young, I. Fonseca, and G. Grimsditch (eds.), 2009: *Blue Carbon.* A Rapid Response Assessment, United Nations Environment Programme, GRID-Arendal, Arendal, Norway, 78 pp.

Nicholls, R.J., 2010: Impacts of and responses to sea-level rise. In: *Understanding Sea-level Rise and Variability* [Church, J.A., P.L. Woodworth, T. Aarup, and W.S. Wilson (eds.)]. Wiley-Blackwell, Chichester, UK and Hoboken, NJ, USA, pp. 17-51.

Nicholls, R.J. and A. Cazenave, 2010: Sea-level rise and its impact on coastal zones. *Science*, **328(5985)**, 1517-1520.

Nicholls, R.J. and R.S.J. Tol, 2006: Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century. *Philosophical Transactions of the Royal Society A*, **364(1841)**, 1073-1095.

Nicholls, R.J., P.P. Wong, V.R. Burkett, J.O. Codignotto, J.E. Hay, R.F. McLean, S. Ragoonaden, and C.D. Woodroffe, 2007: Coastal systems and low-lying areas. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 315-356.

Nicholls, R.J., S. Hanson, C. Herweijer, N. Patmore, S. Hallegatte, J. Corfee-Morlot, J. Château, and R. Muir-Wood, 2008: *Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes*. OECD Environment Working Paper No. 1, OECD Publishing, Paris, France, 62 pp.

Nicholls, R.J., S. Brown, S. Hanson, and J. Hinkel, 2010: *Economics of Coastal Zone Adaptation to Climate Change*. The World Bank Discussion Paper 10, Development and Climate Change Series, The International Bank for Development and Reconstruction / The World Bank, Washington DC, USA, 48 pp.

Nicholls, R.J., N. Marinova, J.A. Lowe, S. Brown, P. Vellinga, D. de Gusmão, J. Hinkel, and R.S.J. Tol, 2011: Sea-level rise and its possible impacts given a 'beyond 4°c world' in the twenty-first century. *Philosophical Transactions of the Royal Society A*, **369(1934)**, 161-181.

Nicholls, R.J., S.E. Hanson, J.A. Lowe, R.A. Warrick, X. Lu, and A.J. Long, 2013: Sea-level scenarios for evaluating coastal impacts. *Wiley Interdisciplinary Reviews: Climate Change*, **5(1)**, 129-150.

Nixon, S.W., 1982: Nutrient dynamics, primary production and fisheries yields of lagoons. In: *Coastal Lagoons: Proceedings of the International Symposium on Coastal Lagoons, Bordeaux, France, 8-14 September, 1981* [Lasserre, P. and H. Postma (eds.)]. *Oceanologica Acta*, **V(Suppl 4)**, 357-371.

Norman, B., 2009: *Planning for Coastal Climate Change: An Insight into International and National Approaches*. Victorian Government Department of Planning and Community Development and Department of Sustainability and Environment, Melbourne, Australia, 62 pp.

Nunn, P.D., 2009: Responding to the challenges of climate change in the Pacific Islands: management and technological imperatives. *Climate Research*, **40(2-3)**, 211-231.

O'Neill, B.C., T.R. Carter, K.L. Ebi, J. Edmonds, S. Hallegatte, E. Kemp-Benedict, E. Kriegler, L. Mearns, R. Moss, K. Riahi, B. van Ruijven, and D. van Vuuren, 2012: *Meeting Report of the Workshop on the Nature and Use of New Socioeconomic Pathways for Climate Change Research, Boulder, CO, November 2-4, 2011*, Integrated Science Program at the National Center for Atmospheric Research (NCAR), Boulder, CO, USA, 37 pp., www.isp.ucar.edu/socio-economic-pathways.

O'Rourke, D. and S. Connolly, 2003: Just oil? The distribution of environmental and social impacts of oil production and consumption. *Annual Review of Environment and Resources*, **28**, 587-617.

Onozuka, D., M. Hashizume, and A. Hagihara, 2010: Effects of weather variability on infectious gastroenteritis. *Epidemiology and Infection*, **138(2)**, 236-343.

Ostrom, E., 2007: A diagnostic approach for going beyond panaceas. *Proceedings of the National Academy of Sciences of the United States of America*, **104(39)**, 15181-15187.

Ostrom, E., 2009: A general framework for analyzing sustainability of social-ecological systems. *Science*, **325(5939)**, 419-422.

Palmer, B.J., T.R. Hill, G.K. Mcgregor, and A.W. Paterson, 2011: An assessment of coastal development and land use change using the DPSIR Framework: case studies from the Eastern Cape, South Africa. *Coastal Management*, **39(2)**, 158-174.

Parry, M., N. Arnell, P. Berry, D. Dodman, S. Fankhauser, C. Hope, S. Kovats, R. Nicholls, D. Satterthwaite, R. Tiffin, and T. Wheeler, 2009: *Assessing the Costs of Adaptation to Climate Change: A Review of the UNFCCC and Other Recent Estimates.* International Institute for Environment and Development (IIED) and Grantham Institute for Climate Change, London, UK, 111 pp.

Parvin, G., F. Takahashi, and R. Shaw, 2008: Coastal hazards and community-coping methods in Bangladesh. *Journal of Coastal Conservation*, **12(4)**, 181-193.

Paul, S. and J. Routray, 2010: Household response to cyclone and induced surge in coastal Bangladesh: coping strategies and explanatory variables. *Natural Hazards*, **57(2)**, 477-499.

Pe'eri, S. and B. Long, 2012: LIDAR technology applied to coastal studies and management. *Journal of Coastal Research*, **SI 62**, 1-5.

Pearce, A.F. and M. Feng, 2013: The rise and fall of the "marine heat wave" off Western Australia during the summer of 2010/11. *Journal of Marine Systems*, **111-112**, 139-156.

Pearce, T., B. Smit, F. Duerden, J.D. Ford, A. Goose, and F. Kataoyak, 2010: Inuit vulnerability and adaptive capacity to climate change in Ulukhaktok, Northwest Territories, Canada. *Polar Record*, **46 (237)**, 157-177.

Peel, C. (ed.), 2010: *Facing Up to Rising Sea-Levels: Retreat? Defend? Attack?* Institution of Civil Engineers (ICE) and Building Futures: Royal Institute of British Architects, London, UK, 27 pp.

Pelling, M., 2011: *Adaptation to Climate Change: From Resilience to Transformation*. Routledge, Abingdon, UK, 224 pp.

Pelling, M. and J.I. Uitto, 2001: Small island developing states: natural disaster vulnerability and global change. *Environmental Hazards*, **3**, 49-62.

Pendleton, L., D.C. Donato, B.C. Murray, S. Crooks, W.A. Jenkins, S. Sifleet, C. Craft, J.W. Fourqurean, J.B. Kauffman, N. Marba, P. Megonigal, E. Pidgeon, D. Herr, D. Gordon, and A. Baldera, 2012: Estimating global "blue carbon" emissions from

conversion and degradation of vegetated coastal ecosystems. *PLoS One*, **7(9)**, e43542, doi:10.1371/journal.pone.0043542.

Penland, S., P.F. Connor, Jr., A. Beall, S. Fearnley, and S.J. Williams, 2005: Changes in Louisiana's Shoreline: 1855-2002. *Journal of Coastal Research*, **SI 44**, 7-39.

Penning-Rowsell, E.C., N. Haigh, S. Lavery, and L. McFadden, 2012: A threatened world city: the benefits of protecting London from the sea. *Natural Hazards*, **66(3)**, 1383-1404.

Perch-Nielson, S.L., 2010: The vulnerability of beach tourism to climate change – an index approach. *Climatic Change*, **100(3-4)**, 579-606.

Perch-Nielson, S.L., B. Amelung, and R. Knutti, 2010: Future climatic resources for tourism in Europe based on the daily Tourism Climatic Index. *Climatic Change*, **103**, 363-381.

Percival, G.S., 2008: *An Assessment of Indigenous Environmental Knowledge (IEK) in the Pacific Region to Improve Resilience Environmental Change*. Climate Change Research Centre, University of New South Wales, Kensington, Australia, 37 pp.

Pérez, Á.A., B.H. Fernández, and R.C. Gatti (eds.), 2010: *Building Resilience to Climate Change: Ecosystem-Based Adaptation and Lessons from the Field*. Ecosystem Management Series No. 9, International Union for Conservation of Nature (IUCN), Gland, Switzerland, 164 pp.

Perry, C.L. and I.A. Mendelssohn, 2009: Ecosystem effects of expanding populations of *Avicennia germinans* in a Louisiana salt marsh. *Wetlands*, **29(1)**, 396-406.

Perry, C.T., G.N. Murphy, P.S. Kench, S.G. Smithers, E.N. Edinger, R.S. Steneck, and P.J. Mumby, 2013: Caribbean-wide decline in carbonate production threatens coral reef growth. *Nature Communications*, **4**, 1402, doi:10.1038/ncomms2409.

Phillips, M.R. and A.L. Jones, 2006: Erosion and tourism infrastructure in the coastal zone: problems, consequences and management. *Tourism Management*, **27**, 517-524.

Pialoux, G., B.-A. Gaüzère, S. Jauréguiberry, and M. Strobel, 2007: Chikungunya, an epidemic arbovirosis. *The Lancet: Infectious Diseases*, **7(5)**, 319-327.

Pilkey, O.H. and R. Young, 2009: *The Rising Sea*. Island Press/Shearwater Books, Washington DC, USA, 209 pp.

Plant, N., H. Stockdon, A. Sallenger, M. Turco, J. East, A. Taylor, and W. Shaffer, 2010: Forecasting hurricane impact on coastal topography. *EOS, Transactions of the American Geophysical Union*, **91(7)**, 65-72.

Polack, E., 2010: *Integrating Climate Change into Regional Disaster Risk Management at the Mekong River Commission*. Strengthening Climate Resilience Discussion Paper 4, Institute of Development Studies, Brighton, UK, 36 pp.

Pollack, J.B., T.A. Palmer, and P.A. Montagna, 2011: Long-term trends in the response of benthic macrofauna to climate variability in the Lavaca-Colorado Estuary, Texas. *Marine Ecology Progress Series*, **436**, 67-80.

Poloczanska, E.S., S.J. Hawkins, A.J. Southward, and M.T. Burrows, 2008: Modeling the response of populations of competing species to climate change. *Ecology*, **89(11)**, 3138-3149.

Poloczanska, E.S., S. Smith, L. Fauconnet, J. Healy, I.R. Tibbetts, M.T. Burrows, and A.J. Richardson, 2011: Little change in the distribution of rocky shore faunal communities on the Australian east coast after 50 years of rapid warming. *Journal of Experimental Marine Biology and Ecology*, **400(1-2)**, 145-154.

Pomeroy, R.S., B.D. Ratner, S.J. Hall, J. Pimoljinda, and V. Vivekanandan, 2006: Coping with disaster: rehabilitating coastal livelihoods and communities. *Marine Policy*, **30(6)**, 786-793.

Pouliotte, J., B. Smit, and L. Westerhoff, 2009: Adaptation and development: livelihoods and climate change in Subarnabad, Bangladesh. *Climate and Development*, **1(1)**, 31-46.

Provoost, P., S. van Heuven, K. Soetaert, R. Laane, and J.J. Middelburg, 2010: Seasonal and long-term changes in pH in the Dutch coastal zone. *Biogeosciences*, **7(11)**, 3869-3878.

Raabe, E.A., L.C. Roy, and C.C. McIvor, 2012: Tampa Bay coastal wetlands: nineteenth to twentieth century tidal marsh-to-mangrove conversion. *Estuaries and Coasts*, **35(5)**, 1145-1162.

Rabalais, N.N., R.E. Turner, R.J. Díaz, and D. Justić, 2009: Climate change and eutrophication of coastal waters. *International Council for the Exploration of the Sea (ICES) Journal of Marine Sciences*, **66**, 1528-1537.

Rabalais, N.N., R.J. Diaz, L.A. Levin, R.E. Turner, D. Gilbert, and J. Zhang, 2010: Dynamics and distribution of natural and human-caused hypoxia. *Biogeosciences*, **7(2)**, 585-619.

Rabbani, M.G., S.H. Rahman, and L. Faulkner, 2013: Impacts of climatic hazards on the small wetland ecosystems (ponds): evidence from some selected areas of coastal Bangladesh. *Sustainability*, **5**, 1510-1521.

Rahman, K.M.M., J. Ensor, and R. Berger, 2009: River erosion and flooding in northern Bangladesh. In: *Understanding Climate Change Adaptation: Lessons from Community-Based Approaches* [Ensor, J. and R. Berger (eds.)]. Practical Action Publishing, Bourton-on-Dunsmore, UK, pp. 39-54.

Raihan, S., M. Huq, Gerstrøm N. Alsted, and M. Andreasen, 2010: *Understanding Climate Change from Below, Addressing Barriers from Above: Practical Experience and Learning from a Community-Based Adaptation Project in Bangladesh.* ActionAid Bangladesh, Dhaka, Bangladesh, 98 pp.

Ramasamy, R. and S.N. Surendran, 2011: Possible impact of rising sea levels on vector-borne infectious diseases. *BMC Infectious Diseases*, **11**, 18, doi:10.1186/1471-2334-11-18.

Ranasinghe, R., D. Callaghan, and M. Stive, 2012: Estimating coastal recession due to sea level rise: beyond the Bruun rule. *Climatic Change*, **110**, 561-574.

Rasheed, M.A. and R.K.F. Unsworth, 2011: Long-term climate-associated dynamics of a tropical seagrass meadow: implications for the future. *Marine Ecology Progress Series*, **422**, 93-103.

Rawlani, A. and B. Sovacool, 2011: Building responsiveness to climate change through community based adaptation in Bangladesh. *Mitigation and Adaptation Strategies for Global Change*, **(16)8**, 845-863.

Reguero, B., F.J. Méndez, and I.J. Losada, 2013: Variability of multivariate wave climate in Latin America and the Caribbean. *Global and Planetary Change*, **100**, 70-84.

Reid, H., T. Cannon, R. Berger, M. Alam, and A. Milligan (eds.), 2009: *Participatory Learning and Action 60: Community Based Adaptation to Climate Change*. International Institute for Environment and Development (IIED), London, UK, 218 pp.

Reusch, T.B.H., A. Ehlers, A. Hämmerli, and B. Worm, 2005: Ecosystem recovery after climatic extremes enhanced by genotypic diversity. *Proceedings of the National Academy of Sciences of the United States of America*, **102(8)**, 2826-2831.

Revell, D.L., R. Battalio, B. Spear, P. Ruggiero, and J. Vandever, 2011: A methodology for predicting future coastal hazards due to sea-level rise on the California coast. *Climatic Change*, **109(Suppl. 1)**, 251-276.

Reynaud, S., N. Leclercq, S. Romaine-Lioud, C. Ferrier-Pages, J. Jaubert, and J. Gattuso, 2003: Interacting effects of CO_2 partial pressure and temperature on photosynthesis and calcification in a scleractinian coral. *Global Change Biology*, **9(11)**, 1660-1668.

Riadh, S.M., R.M. Chowdhury, and A. Ishtiaque, 2012: *Community-based Climate Change Adaptation: Planning through Nishorgo Network.* USAID's Integrated Protected Area Co-Management Project (IPAC), Dhaka, Bangladesh, 35 pp.

Ridgeway, K.R., 2007: Long-term trend and decadal variability of the southward penetration of the East Australian Current. *Geophysical Research Letters*, **34**, L13613, doi:10.1029/2007GL030393.

Rittel, H.W.J. and M.M. Webber, 1973: Dilemmas in a general theory of planning. *Policy Sciences*, **4(2)**, 155-169.

Rivadeneira, M.M. and M. Fernández, 2005: Shifts in southern endpoints of distribution in rocky intertidal species along the south-eastern Pacific coast. *Journal of Biogeography*, **32(2)**, 203-209.

Rodolfo-Metalpa, R., F. Houlbrèque, É. Tambutté, F. Boisson, C. Baggini, F.P. Patti, R. Jeffree, M. Fine, A. Foggo, J.-P. Gattuso, and J. M. Hall-Spencer, 2011: Coral and mollusc resistance to ocean acidification adversely affected by warming. *Nature Climate Change*, **1**, 308-312.

Romieu, E., T. Welle, S. Schneiderbauer, M. Pelling, and C. Vinchon, 2010: Vulnerability assessment within climate change and natural hazard contexts: revealing gaps and synergies through coastal applications. *Sustainability Science*, **5(2)**, 159-170.

Rosenzweig, C., W.D. Solecki, R. Blake, M. Bowman, C. Faris, V. Gornitz, R. Horton, K. Jacob, A. LeBlanc, R. Leichenko, M. Linkin, D. Major, M. O'Grady, L. Patrick, E. Sussman, G. Yohe, and R. Zimmerman, 2011: Developing coastal adaptation to climate change in the New York City infrastructure-shed: process, approach, tools, and strategies. *Climatic Change*, **106**, 93-127.

Rozell, D.J. and T.F. Wong, 2010: Effects of climate change on groundwater resources at Shelter Island (New York State, USA). *Hydrogeology Journal*, **18**, 1657-1665.

Rupp-Armstrong, S. and R.J. Nicholls, 2007: Coastal and estuarine retreat: a comparison of the application of managed realignment in England and Germany. *Journal of Coastal Research*, **23(6)**, 1418-1430.

Ryan, A., R. Gorddard, N. Abel, A.M. Leitch, K.S. Alexander, and R.M. Wise, 2011: *Perceptions of Sea-Level Rise Risk and the Assessment of Managed Retreat Policy: Results from an Exploratory Community Survey in Australia*. The Commonwealth Scientific and Industrial Research Organisation (CSIRO): Climate Adaptation National Research Flagship, Clayton, Australia, 49 pp.

Saito, Y., N. Chaimanee, T. Jarupongsakul, and J.P.M. Syvitski, 2007: Shrinking megadeltas in Asia: sea-level rise and sediment reduction impacts from case study of the Chao Phraya Delta. *Land-Ocean Interaction in the Coastal Zone (LOICZ) INPRINT*, **2007/2**, 3-9.

Sales, R.F.M., 2009: Vulnerability and adaptation of coastal communities to climate variability and sea-level rise: their implications for integrated coastal management in Cavite City, Philippines. *Ocean and Coastal Management*, **52(7)**, 395-404.

Salisbury, J., M. Green, C. Hunt, and J. Campbell, 2008: Coastal acidification by rivers: a new threat to shellfish? *EOS, Transactions, American Geophysical Union*, **89(50)**, 513.

Sallenger, A., R. Morton, C. Fletcher, E.R. Thierler, and P. Howd, 2000: Discussion of 'Sea level rise shown to drive coastal erosion' by Leatherman et al. (2000*). EOS, Transactions of the American Geophysical Union*, **81(38)**, 436.

Sanchez-Arcilla, A., J.A. Jimenez, H.I. Valdemoro, and V. Gracia, 1998: Implications of climatic change on Spanish Mediterranean low-lying coasts: the Ebro Delta case. *Journal of Coastal Research*, **24**, 306-316.

Saroar, M. and J. Routray, 2010: Adaptation in situ or retreat? A multivariate approach to explore the factors that guide the peoples' preference against the impacts of sea level rise in coastal Bangladesh. *Local Environment: The International Journal of Justice and Sustainability*, **15(7)**, 663-686.

Savage, C., S.F. Thrush, A.M. Lohrer, and J.E. Hewitt, 2012: Ecosystem services transcend boundaries: estuaries provide resource subsidies and influence functional diversity in coastal benthic communities. *PLoS One*, **7(8)**, e42708, doi:10.1371/journal.pone.0042708.

Schleupner, C., 2008: Evaluation of coastal squeeze and its consequences for the Caribbean island Martinique. *Ocean and Coastal Management*, **51**, 383-390.

Schmitt, K., T. Albers, T.T. Pham, and S.C. Dinh, 2013: Site-specific and integrated adaptation to climate change in the coastal mangrove zone of Soc Trang Province, Vietnam. *Journal of Coastal Conservation*, **17(3)**, 545-558.

Scott, D., B. Amelung, S. Becken, J.-P. Ceron, G. Dubois, S. Gössling, P. Peeters, and M.C. Simpson, 2008: *Climate Change and Tourism – Responding to Global Challenges*. World Tourism Organization, Madrid, Spain, and United Nations Environment Programme, Paris, France, 256 pp.

Scott, D., M.C. Simpson, and R. Sim, 2012: The vulnerability of Caribbean coastal tourism to scenarios of climate change related to sea level rise. *Journal of Sustainable Tourism*, **20**, 883-898.

Seitzinger, S.P., E. Mayorga, A.F. Bouwman, C. Kroeze, A.H.W. Beusen, G. Billen, G. Van Drecht, E. Dumont, B.M. Fekete, J. Garnier, and J.A. Harrison, 2010: Global river nutrient export: a scenario analysis of past and future trends. *Global Biogeochemical Cycles*, **24(4)**, GB0A08, doi:10.1029/2009GB003587.

Semedo, A., K. Sušelj, A. Rutgersson, and A. Sterl, 2011: A global view on the wind sea and swell climate and variability from ERA-40. *Journal of Climate*, **24(5)**, 1461-1479.

Seneviratne, S.I., N. Nicholls, D. Easterling, C.M. Goodess, S. Kanae, J. Kossin, Y. Luo, J. Marengo, K. McInnes, M. Rahimi, M. Reichstein, A. Sorteberg, C. Vera, and X. Zhang, 2012: Changes in climate extremes and their impacts on the natural physical environment. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 109-230.

Sesil, F.A., F. Karsil, I. Colkesen, and N. Akyol, 2009: Monitoring the changing position of coastlines using aerial and satellite image data: an example from the eastern coast of Trabzon, Turkey. *Environmental Monitoring and Assessment*, **153**, 391-403.

Setiadi, N., J. Birkmann, and P. Buckle (eds.), 2010: *Disaster Risk Reduction and Climate Change Adaptation: Case Studies from South and Southeast Asia*. Studies of the University: Research, Counsel, Education (SOURCE), Publication Series of United Nations Institute for Environment and Human Security (UNU-EHS) No. 14/2010, UNU-EHS, Bonn, Germany, 130 pp.

Seto, K.C., 2011: Exploring the dynamics of migration to mega-delta cities in Asia and Africa: contemporary drivers and future scenarios. *Global Environmental Change: Human and Policy Dimensions*, **21(1)**, S94-S107.

Shaffer, G., S.M. Olsen, and J.O.P. Pedersen, 2009: Long-term ocean oxygen depletion in response to carbon dioxide emissions from fossil fuels. *Nature Geoscience*, **2(2)**, 105-109.

Shepard, C.C., C.M. Crain, and M.W. Beck, 2011: The protective role of coastal marshes: a systematic review and meta-analysis. *PLoS One*, **6(11)**, e27374, doi:10.1371/journal.pone.0027374.

Sheppard, C., D.J. Dixon, M. Gourlay, A. Sheppard, and R. Payet, 2005: Coral mortality increases wave energy reaching shores protected by reef flats: examples from the Seychelles. *Estuarine, Coastal and Shelf Science*, **64(2-3)**, 223-234.

Sherman, K., I.M. Belkin, K.D. Friedland, J. O'Reilly, and K. Hyde, 2009: Accelerated warming and emergent trends in fisheries biomass yields of the world's large marine ecosystems. *Ambio*, **38(4)**, 215-224.

Shipman, B. and T. Stojanovic, 2007: Facts, fictions, and failures of integrated coastal zone management in Europe. *Coastal Management*, **35(2)**, 375-398.

Silverman, J., B. Lazar, L. Cao, K. Caldeira, and J. Erez, 2009: Coral reefs may start dissolving when atmospheric CO_2 doubles. *Geophysical Research Letters*, **36**, L05606, doi:10.1029/2008GL036282.

Simeoni, U. and C. Corbau, 2009: A review of the Delta Po evolution (Italy) related to climatic changes and human impacts. *Geomorphology*, **107**, 64-71.

Simpson, M.C., D. Scott, M. Harrison, N. Silver, E. O'Keeffe, R. Sim, S. Harrison, M. Taylor, G. Lizcano, M. Rutty, H. Stager, J. Oldham, M. Wilson, M. New, J. Clarke, O.J. Day, N. Fields, J. Georges, R. Waithe, and P. McSharry, 2010: *Quantification and Magnitude of Losses and Damages Resulting from the Impacts of Climate Change: Modelling the Transformational Impacts and Costs of Sea Level Rise in the Caribbean (Summary Document)*. United Nations Development Programme (UNDP), Barbados and the Organization of Eastern Caribbean States, Christ Church, Barbados, 266 pp.

Smith, J.M., M.A. Cialone, T.V. Wamsley, and T.O. McAlpin, 2010: Potential impact of sea level rise on coastal surges in southeast Louisiana. *Ocean Engineering*, **37(1)**, 37-47.

Smith, J.R., P. Fong, and R.F. Ambrose, 2006: Dramatic declines in mussel bed community diversity: response to climate change? *Ecology*, **87**, 1153-1161.

Smith, K., 2011: We are seven billion. *Nature Climate Change*, **1(7)**, 331-335.

Smith, S., R. Buddemeier, F. Wulff, D. Swaney, V. Camacho-Ibar, L. David, V. Dupra, J. Kleypas, M. San Diego-McGlone, C. McLaughlin, and P. Sandhei, 2005: C, N, P fluxes in the coastal zone. In: *Coastal Fluxes in the Anthropocene: The Land-Ocean Interactions in the Coastal Zone Project of the International Geosphere-Biosphere Programme* [Crossland C.J., H.H. Kremer, H.J. Lindeboom, J.I. Marshall Crossland, and M.D.A. Le Tissier (eds.)]. Global Change – the IGBP Series, Springer-Verlag, Berlin Heidelberg, Germany, pp. 95-143.

Somero, G.N., 2012: The physiology of global change: linking patterns to mechanism. *Nature Geoscience*, **4**, 39-61.

Sovacool, B., A. D'Agostino, H. Meenawat, and A. Rawlani, 2011: Expert views of climate change adaptation in least developed Asia. *Journal of Environmental Management*, **(97)**, 78-88.

Sovacool, B., A. D'Agostino, A. Rawlani, and H. Meenawat, 2012: Improving climate change adaptation in least developed Asia. *Environmental Science and Policy*, **(21)**, 112-125.

Statham, P.J., 2012: Nutrients in estuaries – an overview and the potential impacts of climate change. *The Science of the Total Environment*, **434**, 213-227.

Sterl, A., H. van den Brink, H. de Vries, R. Haarsma, and E. van Meijgaard, 2009: An ensemble study of extreme storm surge related water levels in the North Sea in a changing climate. *Ocean Science*, **5(3)**, 369-378.

Sterrett, C., 2011: *Review of Climate Change Adaptation Practices in South Asia.* Oxfam Research Report, Oxford, UK, 100 pp.

Stive, M.J.C., L.O. Fresco, P. Kabat, B.W.A.H. Parmet, and C.P. Veerman, 2011: How the Dutch plan to stay dry over the next century. *Proceedings of the Institution of Civil Engineers*, **164(3)**, 114-121.

Stojanovic, T. and R.C. Ballinger, 2009: Integrated coastal management: a comparative analysis of four UK initiatives. *Applied Geography*, **29(1)**, 49-62.

Stojanovic, T. and N. Barker, 2008: Improving governance through local coastal partnerships in the UK. *Geographical Journal*, **174(4)**, 344-360.

Stojanovic, T., R.C. Ballinger, and C.S. Lalwani, 2004: Successful integrated coastal management: measuring it with research and contributing to wise practice. *Ocean and Coastal Management*, **47**, 273-298.

Stokes, D.J., T.R. Healy, and P.J. Cooke, 2010: Expansion dynamics of monospecific, temperate mangroves and sedimentation in two embayments of a barrier-enclosed lagoon, Tauranga Harbour, New Zealand. *Journal of Coastal Research*, **26(1)**, 113-122.

Storbjörk, S., 2010: It takes more to get a ship to change course: barriers for organizational learning and local climate adaptation in Sweden. *Journal of Environmental Policy and Planning*, **12(3)**, 235-254.

Storbjörk, S. and J. Hedren, 2011: Institutional capacity-building for targeting sea-level rise in the climate adaptation of Swedish coastal zone management. Lessons from Coastby. *Ocean and Coastal Management*, **54(3)**, 265-273.

Storlazzi, C.D., E. Elias, M.E. Field, and M.K. Presto, 2011: Numerical modeling of the impact of sea-level rise on fringing coral reef hydrodynamics and sediment transport. *Coral Reefs*, **30**, 83-96.

Stratten, L., M.S. O'Neill, M.E. Kruk, and M.L. Bell, 2008: The persistent problem of malaria: addressing the fundamental causes of a global killer. *Social Science and Medicine*, **67**, 854-862.

Strauss, B.H., 2013: Rapid accumulation of committed sea level rise from global warming. *Proceedings of the National Academy of Sciences of the United States of America*, **110(34)**, 13699-13700.

Stutz, M.L. and O.H. Pilkey, 2011: Open-ocean barrier islands: global influence of climatic, oceanographic, and depositional settings. *Journal of Coastal Research*, **27(2)**, 207-222.

Sumaila, R., W. Cheung, V. Lam, D. Pauly, and S. Herrick, 2011: Climate change impacts on the biophysics and economics of world fisheries. *Nature Climate Change*, **1(9)**, 449-456.

Swanson, R.L. and R.E. Wilson, 2008: Increased tidal ranges coinciding with Jamaica Bay development contribute to marsh flooding. *Journal of Coastal Research*, **24(6)**, 1565-1569.

Syvitski, J.P.M., 2008: Deltas at risk. *Sustainability Science*, **3**, 23-32.

Syvitski, J.P.M. and A. Kettner, 2011: Sediment flux and the Anthropocene. *Philosophical Transactions of Royal Society A*, **369**, 957-975.

Syvitski, J.P.M., C.J. Vorosmarty, A.J. Kettner, and P. Green, 2005: Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science*, **308(5720)**, 376-380.

Syvitski, J.P.M., A.J. Kettner, I. Overeem, E.W.H. Hutton, M.T. Hannon, G.R. Brakenridge, J. Day, C. Vörösmarty, Y. Saito, L. Giosan, and R.J. Nicholls, 2009: Sinking deltas due to human activities. *Nature Geoscience*, **2**, 681-686.

Tabet, L. and L. Fanning, 2012: Integrated coastal zone management under authoritarian rule: an evaluation framework of coastal governance in Egypt. *Ocean and Coastal Management*, **61**, 1-9.

Teatini, P., N. Castelletto, M. Ferronato, G. Gambolati, C. Janna, E. Cairo, D. Marzorati, D. Colombo, A. Ferretti, A. Bagliani, and F. Bottazzi, 2011: Geomechanical response to seasonal gas storage in depleted reservoirs: a case study in the Po River basin, Italy. *Journal of Geophysical Research: Earth Surface*, **116(F2)**, F02002, doi:10.1029/2010JF001793.

Tebaldi, C., B.H. Strauss, and C.E. Zervas, 2012: Modeling sea level rise impacts on storm surges along US coasts. *Environmental Research Letters*, **7**, 014032, doi:10.1088/1748-9326/7/1/014032.

Teneva, L., M. Karnauskas, C.A. Logan, L. Bianucci, J.C. Currie, and J.A. Kleypas, 2011: Predicting coral bleaching hotspots: the role of regional variability in thermal stress and potential adaptation rates. *Coral Reefs*, **31(1)**, 1-12.

Terry, J.P. and A.C. Falkland, 2010: Responses of atoll freshwater lenses to storm-surge overwash in the Northern Cook Islands. *Hydrology Journal*, **18**, 749-759.

Thomsen, J., M.A. Gutowska, J. Saphšrster, A. Heinemann, K. TrŸbenbach, J. Fietzke, C. Hiebenthal, A. Eisenhauer, A. Kšrtzinger, M. Wahl, and F. Melzner, 2010: Calcifying invertebrates succeed in a naturally CO_2 enriched coastal habitat but are threatened by high levels of future acidification. *Marine Biology*, **7(11)**, 3879-3891.

Thomsen, J., I. Casties, C. Pansch, A. Körtzinger, and F. Melzner, 2013: Food availability outweighs ocean acidification effects in juvenile *Mytilus edulis*: laboratory and field experiments. *Global Change Biology*, **19**, 1017-1027.

Timmermann, A., S. McGregor, and F.F. Jin, 2010: Wind effects on past and future regional sea level trends in the southern Indo-Pacific. *Journal of Climate*, **23(16)**, 4429-4437.

Tobey, J., P. Rubinoff, D. Robadue Jr., G. Ricci, R. Volk, J. Furlow, and G. Anderson, 2010: Practicing coastal adaptation to climate change: lessons from integrated coastal management. *Coastal Management*, **38**, 317-335.

Tol, R.S.J., 2002: Estimates of the damage costs of climate change. Part 1: benchmark estimates. *Environmental and Resource Economics*, **21(1)**, 47-73.

Tol, R.S.J., 2007: The double trade-off between adaptation and mitigation for sea level rise: an application of FUND. *Mitigation and Adaptation Strategies for Global Change*, **12(5)**, 741-753.

Törnqvist, T.E., D.J. Wallace, J.E.A. Storms, J.W.R.L. van Dam, M. Blaauw, M.S. Derksen, C.J.W. Klerks, C. Meijneken, and E.M.A. Snijders, 2008: Mississippi Delta subsidence primarily caused by compaction of Holocene strata. *Nature Geoscience*, **1**, 173-176.

Tran, T.T. and V. Nitivattananon, 2011: Adaptation to flood risks in Ho Chi Minh City, Vietnam. *International Journal of Climate Change Strategies and Management*, **3**, 61-73.

Trenhaile, A.S., 2010: Modeling cohesive clay coast evolution and response to climate change. *Marine Geology*, **277**, 11-20.

Trenhaile, A.S., 2011: Predicting the response of hard and soft rock coasts to changes in sea level and wave height. *Climatic Change*, **109**, 599-615.

Tribbia, J. and S.C. Moser, 2008: More than information: what coastal managers need to plan for climate change. *Environmental Science and Policy*, **11(4)**, 315-328.

Tribollet, A., C. Godinot, M. Atkinson, and C. Langdon, 2009: Effects of elevated pCO_2 on dissolution of coral carbonates by microbial euendoliths. *Global Biogeochemical Cycles*, **23(3)**, GB3008, doi:10.1029/2008GB003286.

Trotman, A., R.M. Gordon, S.D. Hutchinson, R. Singh, and D. McRae-Smith, 2009: Policy responses to GEC impacts on food availability and affordability in the Caribbean community. *Environmental Sciences and Policy*, **12**, 529-541.

Tunstall, S. and S. Tapsell, 2007: Local communities under threat: managed realignment at Corton Village, Suffolk. In: *Managing Coastal Vulnerability* [Fadden, L.M., R.J. Nicholls, and E. Penning-Rowsell (eds.)]. Emerald Group Publishing Limited, Bingley, UK, pp. 97-120.

UNCTAD, 2009: *Maritime Transport and the Climate Change Challenge*. TD/B/C.I/MEM.1/2, Note for Multi-year Expert Meeting on Transport and Trade Facilitation, Geneva, Switzerland, 16-18 February 2009, United Nations Conference on Trade and Development (UNCTAD) Secretariat, Geneva, Switzerland, 17 pp.

UNDP, 2010: *Community-based Adaptation to Climate Change Brochure.* United Nations Development Programme (UNDP) Bureau of Development Policy: Energy & Environment Group, UNDP GEF Small Grants Programme, and UNDP GEF Community-Based Adaptation Programme, New York, NY, USA, 2 pp.

UNEP, 2009: *Sustainable Coastal Tourism: An Integrated Planning and Management Approach*. United Nations Environment Programme (UNEP), Paris, France, 154 pp.

UNEP, 2010: *Technologies for Climate Change Adaptation: Coastal Erosion and Flooding*. TNA Guidebook Series, UNEP Risø Centre on Energy, Climate and Sustainable Development, Roskilde, Denmark, 150 pp.

UNISDR, 2009: *Adaptation to Climate Change by Reducing Disaster Risks: Country Practices and Lessons*. Briefing Note 02, United Nations International Strategy for Disaster Reduction (UNISDR), Geneva, Switzerland, 12 pp., www.unisdr.org/files/11775_UNISDRBriefingAdaptationtoClimateCh.pdf.

UNISDR, 2011: *Global Assessment Report on Disaster Risk Reduction: Revealing Risk, Redefining Development*. United Nations International Strategy for Disaster Reduction (UNISDR) Secretariat, Information Press, Oxford, UK, 178 pp.

Unnikrishnan, A.S., M.R.R. Kumar, and B. Sindhu, 2011: Tropical cyclones in the Bay of Bengal and extreme sea level projections along the east coast of India in a future climate scenario. *Current Science,* **101(3)**, 327-331.

Urwin, K. and A. Jordan, 2008: Does public policy support or undermine climate change adaptation? Exploring policy interplay across different scales of governance. *Global Environmental Change*, **18(1)**, 180-191.

USACE, 2011: *Sea-level Change Considerations for Civil Works Programs*. Engineer Circular No. 1165-2-212, U.S. Army Corps of Engineers (USACE), 32 pp.

USAID, 2009: *Adaptation to Coastal Climate Change – A Guidebook for Development Planners*. U.S. Agency for International Development (USAID), Washington, DC, USA, 147 pp.

USCCSP, 2008: *Abrupt Climate Change*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, U.S. Geological Survey, Reston, VA, USA, 459 pp.

Vafeidis, A.T., R.J. Nicholls, L. McFadden, R.S.J. Tol, J. Hinkel, T. Spencer, P.S. Grashoff, G. Boot, and R.J.T. Klein, 2008: A new global coastal database for impact and vulnerability analysis to sea-level rise. *Journal of Coastal Research*, **24(4)**, 917-924.

Vafeidis, A., B. Neumann, J. Zimmermann, and R.J. Nicholls, 2011: *MR9: Analysis of Land Area and Population in the Low-Elevation Coastal Zone (LECZ).* UK Government's Foresight Project, Migration and Global Environmental Change, Government Office for Science, London, UK, 171 pp.

van Hooidonk, R., J.A. Maynard, and S. Planes, 2013: Temporary refugia for coral reefs in a warming world. *Nature Climate Change*, **3**, 508-511.

van Kleef, E., H. Bambrick, and S. Hales, 2010: The geographic distribution of dengue fever and the potential influence of global climate change. *TropIKA.net*, journal.tropika.net/pdf/tropika/2010nahead/a01v2n1.pdf.

van Vuuren, D.P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, T. Masui, M. Meinshausen, N. Nakićenović, S.J. Smith, and S.K. Rose, 2011: The representative concentration pathways: an overview. *Climatic Change*, **109(1)**, 5-31.

van Vuuren, D.P., K. Riahi, R. Moss, J. Edmonds, A. Thomson, N. Nakićenović, T. Kram, F. Berkhout, R. Swart, A. Janetos, S.K. Rose, and N. Arnell, 2012: A proposal for a new scenario framework to support research and assessment in different climate research communities. *Global Environmental Change*, **22**, 21-35.

Vaquer-Sunyer, R. and C.M. Duarte, 2011: Temperature effects on oxygen thresholds for hypoxia in marine benthic organisms. *Global Change Biology*, **17(5)**, 1788-1797.

Vignola, R., B. Locatelli, C. Martinez, and P. Imbach, 2009. Ecosystem-based adaptation to climate change: what role for policy-makers, society and scientists? *Mitigation and Adaptation Strategies for Global Change*, **14(8)**, 691-696.

Vineis, P., Q. Chan, and A. Khan, 2011: Climate change impacts on water salinity and health. *Journal of Epidemiology and Global Health*, **1(1)**, 5-10.

Waldbusser, G.G., H. Bergschneider, and M.A. Green, 2010: Size-dependent pH effect on calcification in post-larval hard clam *Mercenaria* spp. *Marine Ecology Progress Series*, **417**, 171-182.

Walling, D.E., 2006: Human impact on land-ocean sediment transfer by the world's rivers. *Geomorphology*, **79 (3-4)**, 192-216.

Walling, D.E., 2012: The role of dams in the global sediment budget. In: *Erosion and Sediment Yields in the Changing Environment. Proceedings the IAHS-ICCE International Symposium held at the Institute of Mountain Hazards and Environment, CAS-Chengdu, China, 11–15 October 2012*. International Association of Hydrological Sciences (IAHS), IAHS-AISH Publication 356, Rennes, France, pp. 3-11.

Walling, D.E. and D. Fang, 2003: Recent trends in the suspended sediment loads of the world's rivers. *Global and Planetary Change*, **39**, 111-126.

Walsh, K.J.E., K.L. McInnes, and J.L. McBride, 2012: Climate change impacts on tropical cyclones and extreme sea levels in the South Pacific – a regional assessment. *Global and Planetary Change*, **80-81**, 149-164.

Walters, C., 1986: *Adaptive Management of Renewable Resources*. MacMillan, New York, NY, USA, 374 pp.

Walters, C., 1997: Challenges in adaptive management of riparian and coastal ecosystems. *Ecology and Society*, **1(2)**, 1, www.consecol.org/vol1/iss2/art1/.

Wang, S., R. McGrath, J. Hanafin, P. Lynch, T. Semmler, and P. Nolan, 2008: The impact of climate change on storm surges over Irish waters. *Ocean Modelling*, **25(1-2)**, 83-94.

Wassmann, R., S.V.K. Jagadish, K. Sumfleth, H. Pathak, G. Howell, A. Ismail, R. Serraj, E. Redona, R.K. Singh, and S. Heuer, 2009: Chapter 3: Regional vulnerability of climate change impacts on Asian rice production and scope for adaptation. In: *Advances in Agronomy, Vol. 102* [Sparks, D.L. (ed.)]. Elsevier Science and TechnologyAcademic Press, Waltham, MA, USA, pp. 91-133.

Webb, A.P. and P.S. Kench, 2010: The dynamic response of reef islands to sea-level rise: evidence from multi-decadal analysis of island change in the Central Pacific. *Global and Planetary Change*, **72**, 234-246.

Webb, M.D. and K.W.F. Howard, 2011: Modeling the transient response of saline intrusion to rising sea-levels. *Ground Water*, **49(4)**, 560-569.

Webster, I.T. and G.P. Harris, 2004: Anthropogenic impacts on the ecosystems of coastal lagoons: modelling fundamental biogeochemical processes and management implications. *Marine and Freshwater Research*, **55**, 67-78.

Wernberg, T., B.D. Russell, M.S. Thomsen, C.F. Gurgel, C.J. Bradshaw, E.S. Poloczanska, and S.D. Connell, 2011a: Seaweed communities in retreat from ocean warming. *Current Biology*, **21(21)**, 1828-1832.

Wernberg, T., B.D. Russell, P.J. Moore, S.D. Ling, D.A. Smale, A. Campbell, M.A. Coleman, P.D. Steinberg, G.A. Kendrick, and S.D. Connell, 2011b: Impacts of climate change in a global hotspot for temperate marine biodiversity and ocean warming. *Journal of Experimental Marine Biology and Ecology*, **400(1-2)**, 7-16.

Wetz, M.S. and H.W. Paerl, 2008: Estuarine phytoplankton responses to hurricanes and tropical storms with different characteristics (trajectory, rainfall, winds). *Estuaries and Coasts*, **31(2)**, 419-429.

White, I. and T. Falkland, 2010: Management of freshwater lenses on small Pacific islands. *Hydrogeology Journal*, **18**, 227-246.

White, I., T. Falkland, P. Perez, A. Dray, T. Metutera, E. Metia, and M. Overmars, 2007: Challenges in freshwater management in low coral atolls. *Journal of Cleaner Production*, **15**, 1522-1528.

Wilby, R.L., R.J. Nicholls, R. Warren, H.S. Wheater, D. Clarke, and R.J. Dawson, 2011: Keeping nuclear and other coastal sites safe from climate change. *Proceedings of the Institution of Civil Engineers*, **164(3)**, 129-136.

Wisshak, M., C. Schönberg, A. Form, and A. Freiwald, 2012: Ocean acidification accelerates reef bioerosion. *PLoS ONE*, **7(9)**, e45124, doi:10.1371/journal.pone.0045124.

Woodroffe, C.D. and C.V. Murray-Wallace, 2012: Sea-level rise and coastal change: the past as a guide to the future. *Quaternary Science Reviews*, **54**, 4-11.

Wootton, J.T. and C.A. Pfister, 2012: Carbon system measurements and potential climatic drivers at a site of rapidly declining ocean pH. *PLoS ONE*, **7(12)**, e53396, doi:10.1371/journal.pone.0053396.

Wootton, J.T., C.A. Pfister, and J.D. Forester, 2008: Dynamic patterns and ecological impacts of declining ocean pH in a high-resolution multi-year dataset. *Proceedings of the National Academy of Sciences of the United States of America*, **105**, 18848-18853.

World Bank, 2011: *The Cost of Adapting to Extreme Weather Events in a Changing Climate*. Bangladesh Development Series Paper No. 67845, The World Bank, Dhaka, Bangladesh and Washington DC, USA, 41 pp.

Wu, H.Y., D.H. Zou, and K.S. Gao, 2008: Impacts of increased atmospheric CO_2 concentration on photosynthesis and growth of micro- and macro-algae. *Science in China Series C: Life Sciences*, **51**, 1144-1150.

Xia, J., R.A. Falconer, B. Lin, and G. Tan, 2011: Estimation of future coastal flood risk in the Severn Estuary due to a barrage. *Journal of Flood Risk Management*, **4(3)**, 247-259.

Yamano, H., K. Sugihara, and K. Nomura, 2011: Rapid poleward range expansion of tropical reef corals in response to rising sea surface temperatures. *Geophysical Research Letters*, **38(4)**, L04601, doi:10.1029/2010GL046474.

Yang, S.L., J.D. Milliman, P. Li, and K. Xu, 2011: 50,000 dams later: erosion of the Yangtze River and its delta. *Global and Planetary Change*, **75**, 14-20.

Yara, Y., M. Vogt, M. Fujii, H. Yamano, C. Hauri, M. Steinacher, N. Gruber, and Y. Yamanaka, 2012: Ocean acidification limits temperature-induced poleward expansion of coral habitats around Japan. *Biogeosciences*, **9**, 4955-4968.

Yasuhara, K., S. Murakami, N. Mimura, H. Komine, and J. Recio, 2007: Influence of global warning on coastal infrastructural instability. *Sustainability Science*, **2**, 13-25.

Yin, J, Z. Yin, J. Wang, and S. Xu, 2012: National assessment of coastal vulnerability to sea-level rise for the Chinese coast. *Journal Coastal Conservation*, **16(1)**, 123-133.

Yohe, G., K. Knee, and P. Kirshen, 2011: On the economics of coastal adaptation solutions in an uncertain world. *Climatic Change*, **106(1)**, 71-92.

Yoo, G., J.H. Hwang, and C. Choi, 2011: Development and application of a methodology for vulnerability assessment of climate change in coastal cities. *Ocean and Coastal Management*, **54(7)**, 524-534.

Zeitlin, H.L., I. Meliane, S. Davidson, T. Sandwith, and J. Hoekstra, 2012: Ecosystem-based adaptation in marine and coastal ecosystems. *Environmental Sciences*, **25**, 1-10.

Zevenbergen, C., S. van Herk, J. Rijke, P. Kabat, P. Bloemen, R. Ashley, A. Speers, B. Gersonius, and W. Veerbeek, 2013: Taming global flood disasters. Lessons learned from Dutch experience. *Natural Hazards*, **65**, 1217-1225.

Zhang, J., D. Gilbert, A.J. Gooday, L. Levin, S.W.A. Naqvi, J.J. Middelburg, M. Scranton, W. Ekau, A. Peña, B. Dewitte, T. Oguz, P.M.S. Monteiro, E. Urban, N.N. Rabalais, V. Ittekkot, W.M. Kemp, O. Ulloa, R. Elmgren, E. Escobar-Briones, and A.K. Van der Plas, 2010: Natural and human-induced hypoxia and consequences for coastal areas: synthesis and future development. *Biogeosciences*, **7(5)**, 1443-1467.

Zhang, X. and J.A. Church, 2012: Sea level trends, interannual and decadal variability in the Pacific Ocean. *Geophysical Research Letters*, **39(21)**, doi:10.1029/2012GL053240.

Zhang, X., F.W. Zwiers, and G. Li, 2004: Monte Carlo experiments on the detection of trends in extreme values. *Journal of Climate*, **17**, 1945-1952.

Zhang, Y., P. Bi, J.E. Hiller, Y. Sun, and P. Ryan, 2007: Climate variations and bacillary dysentery in northern and southern cities of China. *Journal of Infection*, **55(2)**, 194-200.

Zhu, G., X. Xu, Z. Ma, L. Xu, and J.H. Porter, 2012: Spatial dynamics and zoning of coastal land-use change along Bohai Bay, China, during 1979-2008. *Journal of Coastal Research*, **28(5)**, 1186-1196.

6 Ocean Systems

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This chapter should be cited as:

Pörtner, H.-O., D.M. Karl, P.W. Boyd, W.W.L. Cheung, S.E. Lluch-Cota, Y. Nojiri, D.N. Schmidt, and P.O. Zavialov, 2014: Ocean systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 411-484.

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Executive Summary

Ocean ecosystems have responded and will continue to respond to climate changes of different rates, magnitudes, and durations (*virtually certain*). Human societies depend on marine ecosystem services, which are sensitive to climate change (*high confidence*), in particular the provisioning of food (fisheries and aquaculture) and other natural resources; nutrient recycling; regulation of global climate including production of oxygen (O_2) and removal of atmospheric carbon dioxide (CO_2); protection from extreme weather and climate events; and aesthetic, cultural, and supporting services. {6.3, 6.4, 6.5}

Climate change alters physical, chemical, and biological properties of the ocean (*very high confidence*). Oceanic drivers include salinity, circulation, temperature, carbon dioxide (CO_2), oxygen (O_2), nutrients, and light. These drivers shape the physiological performance of individual cells and organisms and ultimately determine ecosystem composition, spatial structure, and functioning. {6.1.1, 6.3}

The fossil record and present field and laboratory observations confirm links between key environmental drivers and responses of ocean ecosystems to climate change (*high confidence*). For millions of years in Earth history, natural climate change at rates slower than today's anthropogenic change has led to significant ecosystem shifts (*high confidence*), including species emergences and extinctions (*high confidence*). Contemporary multi-decadal natural climate variations associated with regional transient warming periods by 1°C have led to fundamental restructuring of ecosystems and large socioeconomic implications (*high confidence*). {6.1.2, 6.3.1, 6.4}

Vulnerability of most organisms to warming is set by their physiology, which defines their limited temperature ranges and hence their thermal sensitivity (*high confidence*). Temperature defines the geographic distribution of many species and their responses to climate change. Shifting temperature means and extremes alter habitat (e.g., sea ice and coastal), and cause changes in abundance through local extinctions and latitudinal expansions or shifts (*very high confidence*). Vulnerability is greatest in polar animals owing to their narrow temperature ranges (*medium confidence*) and in tropical species living close to upper thermal limits (*medium confidence*). Although genetic adaptation occurs (*medium confidence*), the capacity of present-day fauna and flora to compensate for or keep up with the rate of ongoing thermal change is limited (*low confidence*). {6.3.1, 6.3.5, 6.5.2}

The warming-induced shifts in the abundance, geographic distribution, migration patterns, and timing of seasonal activities of species (*very high confidence*) have been and will be paralleled by a reduction in their maximum body size (*medium confidence*). This has resulted and will further result in changing interactions between species, including competition and predator-prey dynamics (*high confidence*). Numerous observations over the last decades in all ocean basins show global-scale changes including large-scale distribution shifts of species (*very high confidence*) and altered ecosystem composition (*high confidence*) on multi-decadal time scales, tracking climate trends. The distribution and abundance of many fishes and invertebrates have shifted poleward and/or to deeper, cooler waters (*high confidence*). Poleward displacements of phyto- and zooplankton have occurred by hundreds of kilometers per decade (*high confidence*). Some warm-water corals and their reefs have responded with species replacement, bleaching, and a decreased coral cover causing habitat loss (*high confidence*). While marine reptiles such as turtles encounter direct effects of warming, impacts to seabirds and marine mammals are mostly indirect through effects of warming on their prey (*high confidence*). {6.3.1, 6.3.7, 6.5, Boxes CC-CR, CC-MB}

In response to further warming by 1°C or more by the mid-21st century and beyond, ocean-wide changes in ecosystem properties are projected to continue (*high confidence*). Large irreversible shifts in the spatial distribution of species and seasonal timing of their activities (feeding, growth, development, behaviors, and productivity) will have implications for species composition, and ecosystem goods and services. {6.3.1, 6.4, 6.5, 6.6}

By the mid-21st century, the spatial shifts of marine species will cause species richness to increase at mid- and high latitudes (*high confidence*) and to decrease at tropical latitudes (*medium confidence*), resulting in global redistribution of catch potential for fishes and invertebrates, with implications for food security (*medium confidence*). Animal displacements are projected to lead to high-latitude invasions and high local extinction rates in the tropics and semi-enclosed seas. This will cause a 30 to 70% increase in the fisheries yield of some high-latitude regions by 2055 (relative to 2005), a redistribution at mid-latitudes, but a drop of 40–60% in the tropics and the Antarctic, based on 2°C warming above preindustrial values (*medium confidence* in the direction of trends in fisheries yields, *low confidence* in

the magnitude of change). If a decrease in global net primary production (NPP) or a shift toward smaller primary producers occurs, the overall fisheries catch potential may also decrease. {6.3.1-4, 6.4.1, 6.5.1-4}

Open ocean NPP is projected to fall globally depending on RCP scenario (*medium confidence*). The estimated decrease will occur by up to 9% by 2100 under the RCP8.5 business-as-usual climate scenario (relative to 1990, *low confidence*). The oceans currently provide about half of global NPP. Environmental controls on NPP include temperature, CO_2, nutrient supply, and light (through cloud cover, mixed layer depth), all of which will be altered (WGI AR5 Section 6.3). Present observations indicate increasing NPP at high (Arctic) latitudes (*medium confidence*), projected to continue beyond 2100 (*medium confidence*). This increase is offset by a decrease at temperate and tropical latitudes (*medium confidence*). Poor representation of shelf and coastal regions hamper projections in global NPP models for near-shore waters, reducing confidence in global projections. {6.3.4, 6.5.1, Box CC-PP}

Large-scale processes and climatic feedbacks sustained by microbes (bacteria, archaea, unicellular algae, and protozoans) play key roles in marine ecosystems (e.g., carbon and nitrogen (N_2) fixation or nutrient recycling) and will be altered by climate change (*medium confidence*). Identifying which microbial species, groups, and processes are being affected and how these will be altered is difficult, as these organisms and their responses to environmental change are extremely diverse and often modulated by biological interactions or changes in circulation and nutrient supply (*limited evidence*, *low agreement*). Warming will cause species-specific responses, such as enhancing metabolic rates and exceeding thermal tolerances, which will affect abundance, distribution, and community structure. Warmer, CO_2- and nutrient-enriched coastal oceans may stimulate harmful algal blooms (*medium confidence*), and the redistribution of certain microbes causing diseases such as cholera (*medium confidence*). {6.3, 6.4.2}

Rising atmospheric CO_2 over the last century and into the future not only causes ocean warming but also changes carbonate chemistry in a process termed ocean acidification (WGI AR5 Sections 3.8.2, 6.4.4). Impacts of ocean acidification range from changes in organismal physiology and behavior to population dynamics (*medium* to *high confidence*) and will affect marine ecosystems for centuries if emissions continue (*high confidence*). Laboratory and field experiments as well as field observations show a wide range of sensitivities and responses within and across organism phyla (*high confidence*). Most plants and microalgae respond positively to elevated CO_2 levels by increasing photosynthesis and growth (*high confidence*). Within other organism groups, vulnerability decreases with increasing capacity to compensate for elevated internal CO_2 concentration and falling pH (*low* to *medium confidence*). Among vulnerable groups sustaining fisheries, highly calcified corals, mollusks, and echinoderms are more sensitive than crustaceans (*high confidence*) and fishes (*low confidence*). Trans-generational or evolutionary adaptation has been shown in some species, reducing impacts of projected scenarios (*low* to *medium confidence*). Limits to adaptive capacity exist but remain largely unexplored. {6.3.2, Box CC-OA}

Few field observations conducted in the last decade demonstrate biotic responses attributable to anthropogenic ocean acidification, as in many places these responses are not yet outside their natural variability and may be influenced by confounding local or regional factors. Shell thinning in planktonic foraminifera and in Southern Ocean pteropoda has been attributed fully or in part to acidification trends (*medium* to *high confidence*). Coastward shifts in upwelling CO_2-rich waters of the Northeast Pacific cause larval oyster fatalities in aquacultures (*high confidence*) or shifts from mussels to fleshy algae and barnacles (*medium confidence*), providing an early perspective on future effects of ocean acidification. This supports insight from volcanic CO_2 seeps as natural analogs that macrophytes (seaweeds and seagrasses) will outcompete calcifying organisms. During the next decades ecosystems, including cold- and warm-water coral communities, are at increasing risk of being negatively affected by ocean acidification, especially as ocean acidification will be combined with rising temperature extremes (*medium* to *high confidence*, respectively). {6.1.2, 6.3.2, 6.3.5}

The expansion of hypoxic regions termed Oxygen Minimum Zones (OMZs) and anoxic "dead zones," observed over the last 50 years and projected into the future under climate change, especially if combined with nutrient enrichment (eutrophication), will constrain the habitat of O_2-dependent organisms and benefit anaerobic microbes (*medium confidence*). Hypoxia tolerance varies among species and is influenced by temperature, elevated CO_2, food consumption, and O_2 demand (*high confidence*). Warming-induced stratification limits the exchange of gases between water layers. Enhanced oxygen consumption by heterotrophic organisms depletes the oxygen further, causing a community shift toward lower species richness and hypoxia-tolerant specialists. Under extreme hypoxia ecosystems are

dominated by microbes. These OMZs are also characterized by microbial removal of fixed nitrogen (denitrification), which can significantly reduce the low-latitude nutrient inventories with implications for regional productivity. {6.3.3, 6.3.5}

The climate-change-induced intensification of ocean upwelling in some eastern boundary systems, as observed in the last decades, may lead to regional cooling rather than warming of surface waters and cause enhanced productivity (*medium confidence*), but also enhanced hypoxia, acidification, and associated biomass reduction in fish and invertebrate stocks. Owing to contradictory observations there is currently uncertainty about the future trends of major upwelling systems and how their drivers (enhanced productivity, acidification, and hypoxia) will shape ecosystem characteristics (*low confidence*). {6.1.1, 6.3.2, 6.3.3, 6.3.5-6, Box CC-UP}

Environmental drivers acting simultaneously on ocean biota* often lead to interactive effects and complex responses (*high confidence*). Interactions of temperature, ocean acidification, and hypoxia narrow thermal ranges and enhance sensitivity to temperature extremes in organisms such as corals, coralline algae, mollusks, crustaceans, and fishes (*high confidence*). In primary producers, light and individual nutrients can also interact with temperature and acidification. Combined warming and ocean acidification reduce calcification in warm-water corals (*high confidence*). Ocean acidification will alter availability of trace metals (*low confidence*). (*The term biota encompasses the organisms of a region, habitat, or geological period.) {6.3.2.2, 6.3.5, 6.5.2}

The combination and often amplification of global and regional climate change and local anthropogenic drivers result in enhanced vulnerability of natural and human systems (*high confidence*). Major regional and local drivers include fishing, pollution, and eutrophication. {6.3.5, 6.4, 6.5}

The progressive redistribution of species and the reduction in marine biodiversity in sensitive regions and habitats puts the sustained provision of fisheries productivity and other ecosystem services at risk, which will increase due to warming by 1°C or more by 2100 compared to the present (*high confidence*). Human societies respond with limited adaptive capacity. Socioeconomic vulnerability is highest in developing tropical countries involving a risk of reduced supplies, income, and employment from marine fisheries (*high confidence*). This emphasizes disparities in food security between developed and underdeveloped nations. {6.4.1, 6.5}

With continuing climate change, local adaptation measures (such as conservation) or a reduction in human activities (such as fishing) may not sufficiently offset global-scale effects on marine ecosystems (*high confidence*). Effects of climate change will thus complicate management regimes such as of marine protected areas once species undergo distributional shifts. This increases the vulnerabilities of marine ecosystems and fisheries. {6.4.2.1}

Geoengineering approaches involving manipulation of the ocean to ameliorate climate change (such as nutrient fertilization, binding of CO_2 by enhanced alkalinity, or direct CO_2 injection into the deep ocean) have very large environmental and associated socioeconomic consequences (*high confidence*). Some actually require purposeful alteration of ocean ecosystems for implementation. Alternative methods focusing on solar radiation management (SRM) leave ocean acidification largely unabated as they cannot mitigate CO_2 emissions. {6.4.2}

6.1. Introduction: Point of Departure, Observations, and Projections

The oceans cover about 71% of Earth's surface to an average depth of 3700 m. Their importance for life on Earth, including humans, is vast (FAQ 6.1). Marine habitats display natural variability on various spatial and temporal scales but a dearth of long-term observational data from the vast open oceans limits our understanding of the causes and ecological consequences of this variability. The available information indicates that climate controls ocean temperatures, chemistry, circulation, upper ocean stratification, nutrient supply, and sunlight exposure. These drivers affect marine ecosystems through direct effects on organisms, amplified by their changing interactions with other species. Food webs are modified by changes in phytoplankton growth and the availability of live organisms or their decomposing bodies, that is, debris or dissolved organic matter, as food to (chemo-)heterotrophs (organisms gaining energy by feeding on organic matter). Organismal responses lead to changes in biogeochemical processes, such as the carbon cycle, and in biological diversity and the services the oceans provide.

Some impacts of climate change on marine ecosystems and their services were addressed in the IPCC Fourth Assessment Report (AR4): WGII Chapters 4 to 6 (ecosystems, food, coastal areas), and regional chapters, for example, 15 (polar regions) and 16 (small islands). The ecosystem assessment in WGII AR4 Chapter 4 focused on terrestrial, coastal, and marine systems, their properties, goods, and services. It emphasized the difficulty in assessing future ecosystem responses as a result of ecosystem complexity, different vulnerabilities of species, and ecosystem-specific, critical thresholds associated with nonlinear responses to environmental change. Focusing on terrestrial ecosystems, WGII AR4 Chapter 4 concluded that more than 2°C to 3°C warming above preindustrial levels causes high extinction risks to 20 to 30% of present-day species (*medium confidence*), paralleled by substantial changes in ecosystem structure and functioning (*high confidence*). The authors projected that a wide range of planktonic and benthic calcifiers will be impacted by ocean warming (*very high confidence*) and acidification (*medium confidence*), particularly in the Southern Ocean. They characterized sea ice and coral reef biomes as highly vulnerable. Key uncertainties identified in AR4 were the incomplete knowledge of ocean acidification (addressed in present Section 6.3.2), synergistic effects and their mechanisms (Section 6.3.5), biotic feedbacks to the climate system (Section 6.4), and the impacts of interactions between climate change, human uses, and ecosystem management (Section 6.4.2).

Much more than in previous IPCC reports (Figure 1-2), impacts on the oceans are a focus in AR5. This allows for a more comprehensive discussion of phenomena and impacts, as well as the associated uncertainties and the levels of confidence in observed and projected changes. The present chapter focuses on the general principles and processes characterizing climate change impacts on ocean systems and on the uses of these systems by human societies. For projections of responses to climate change, the chapter also assesses our understanding of underlying functional mechanisms causing change across all levels of biological organization, from molecules to organisms to ecosystems. As the ocean is a heterogeneous environment, the comparison of major ocean regions is required to understand variability and differences in key processes and carbon inventories (Box CC-PP, Figure 1). We discuss the changes and variability in the ocean's principal physical and chemical properties and assess knowledge drawn from paleo- and historical to present observations. We develop a conceptual framework for analyzing

Frequently Asked Questions

FAQ 6.1 | Why are climate impacts on oceans and their ecosystems so important?

Oceans create half the oxygen (O_2) we use to breathe and burn fossil fuels. Oceans provide about 17% of the animal protein consumed by the world's human population, or almost 20% of that protein consumed by 3 billion people. Oceans are home to species and ecosystems valued in tourism and for recreation. The rich biodiversity of the oceans offers resources for innovative drugs or biomechanics. Ocean ecosystems such as coral reefs and mangroves protect the coastlines from tsunamis and storms. About 90% of the goods the world uses are shipped across the oceans. All these activities are affected by climate change.

Oceans play a major role in global climate dynamics. Oceans absorb 93% of the heat accumulating in the atmosphere, and the resulting warming of oceans affects most ecosystems. About a quarter of all the carbon dioxide (CO_2) emitted from the burning of fossil fuels is absorbed by oceans. Plankton convert some of that CO_2 into organic matter, part of which is exported into the deeper ocean. The remaining CO_2 causes progressive acidification from chemical reactions between CO_2 and seawater, acidification being exacerbated by nutrient supply and with the spreading loss of O_2 content. These changes all pose risks for marine life and may affect the oceans' ability to perform the wide range of functions that are vitally important for environmental and human health.

The effects of climate change occur in an environment that also experiences natural variability in many of these variables. Other human activities also influence ocean conditions, such as overfishing, pollution, and nutrient runoff via rivers that causes eutrophication, a process that produces large areas of water with low oxygen levels (sometimes called "dead zones"). The wide range of factors that affect ocean conditions and the complex ways these factors interact make it difficult to isolate the role any one factor plays in the context of climate change, or to identify with precision the combined effects of these multiple drivers.

effects on organisms and ecosystems and assess present knowledge derived from experiments, field studies, and numerical model projections mostly using Representative Concentration Pathways (RCPs) of climate change scenarios to provide trajectories of climate change drivers (Moss et al., 2010). Finally, we assess the implications of such changes for ecosystem services, and identify plausible socioeconomic consequences.

Assessing climate change impacts on coastal systems is the topic of Chapter 5. An integrative treatment of regional climate changes and impacts in seven key ocean regions is the focus of regional Chapter 30. Marine issues are also included in regional Chapters 22 to 29, with a focus on polar oceans (Chapter 28) and small islands (Chapter 29). Topics important to several chapters, such as ocean acidification, upwelling systems, primary productivity, changes in biogeography, and coral reefs, are discussed in joint assessments presented in the respective cross-chapter boxes.

6.1.1. Changes in Physical and Chemical Variables

Trends in ocean conditions over the last 60 years reflect significant human impacts beyond natural variability on temperature, salinity, dissolved inorganic carbon and oxygen content, pH, and other properties of the upper ocean (e.g., Pierce et al., 2012; Sen Gupta and McNeil, 2012; WGI AR5 Section 3.8, Table 10.1). With climate change, marine ecosystems are and will be exposed to rising temperature, ocean acidification, expansion of hypoxic zones, and other environmental drivers changing concomitantly.

6.1.1.1. Temperature and Salinity

Over the last 39 years, oceans have warmed at average rates of >0.1°C per decade in the upper 75 m and 0.015°C per decade at 700 m depth (WGI AR5 Section 3.2.2, Figure 3.1). Trends differ regionally, seasonally, and interannually (WGI AR5 Section 2.7; for ocean regions see Section 30.5 in the present volume). Temperature changes are particularly large at El Niño-Southern Oscillation (ENSO) with high (3- to 4-year) and low (5- to 7-year) frequencies, and on multi-decadal scales (>25 years, Figure 6-1). The strongest warming trends are found at high latitudes where most of the inter-decadal variability occurs, while tropical oceans are dominated by interannual frequencies. Global climate models have explored changes in different frequency domains, but their spatial resolution is poor (WGI AR5 Sections 11.3.3, 12.4.7).

Temperature variations are often accompanied by changes in salinity. Increased salinity results from reduced precipitation relative to evaporation, for example, above the thermoclines (layer separating the upper mixed layer from deeper water where temperature and density change rapidly with depth) of subtropical gyres at mid- to low latitudes since 1950 (WGI AR5 Chapter 3). Decreased salinity due to enhanced precipitation relative to evaporation has occurred at some tropical and higher latitudes, exacerbated by sea ice melt (Durack et al., 2012). Both warming and freshening cause enhanced density stratification, a trend projected to continue into the 21st century (WGI AR5 Chapter 3, Section 11.3.3, Figure 12.34; Helm et al., 2010). Mean sea surface temperature in 2090 will be 2.7°C warmer than in 1990 (RCP8.5; WGI AR5 Chapter 12; Bopp et al., 2013).

6.1.1.2. Carbon Dioxide-induced Acidification

Rising carbon dioxide (CO_2) concentrations in air (given as partial pressures, $pCO2$, in µatm) cause increasing upper ocean CO_2 levels (Watson et al., 2009). Starting from a preindustrial value of 280 µatm atmospheric pCO_2 levels will have reached around 500 µatm by 2050 following the Special Report on Emissions Scenarios (SRES; IPCC, 2000) and all RCPs (Moss et al., 2010; Meinshausen et al., 2011). By 2100 values are projected to reach between 420 µatm and 940 µatm depending on the RCP. The rise in pCO_2 causes ocean acidification (OA), measured as a decline in water pH (negative log of proton concentration), accompanied by a fall in both carbonate ion (CO_3^{2-}) concentration and the saturation states (Ω) of various calcium carbonates ($CaCO_3$; Zeebe and Westbroek, 2003; WGI AR5 Section 3.8.2, Box 3.2, Chapter 6, Figure 6.29). Hence, the seawater solubilities of three forms of $CaCO_3$, namely calcite, magnesium-calcite, and aragonite, increase. These minerals are important components of shells and skeletons of many marine organisms (Section 6.3.2).

Ocean acidification occurs on a background of natural temporal and spatial variability of pH, pCO_2, and Ω. In the open ocean, the mean pH (total scale, pH_T) of surface waters presently ranges between 7.8 and 8.4 (WGI AR5 Section 3.8.2). In stratified mid-water layers, largely isolated from gas exchange between surface waters and air, decomposition of organic material leads to lowered oxygen (O_2) and elevated CO_2 levels (Paulmier et al., 2011) associated with lower pH values. The few existing field data of sufficient duration, resolution, and accuracy (WGI AR5 Figure 3.18) show that trends in anthropogenic OA clearly deviate from the envelope of natural variability (Friedrich et al., 2012). OA presently ranges between –0.0013 and –0.0024 pH_T units per year (WGI AR5 Section 3.8.2, Table 3.2, Box 3.2; Dore et al., 2009). Average surface ocean pH has decreased by more than 0.1 units below the preindustrial average of 8.17. By 2100 pH is expected to change by –0.13, –0.22, –0.28, and –0.42 pH_T units, at CO_2 levels of 421, 538, 670, and 936 ppm under RCP2.6, 4.5, 6.0, and 8.5 climate scenarios, respectively (WGI AR5 Figure 6.28). The rate of acidification in surface waters varies regionally and is 50% higher in the northern North Atlantic than in the subtropical Atlantic (Olafsson, 2009). Salinity reduction caused by ice melt or excess precipitation (Jacobs and Giulivi, 2010; Vélez-Belchí et al., 2010) exacerbates OA by diluting the concentrations of substances acting as buffers (Steinacher et al., 2009; Denman et al., 2011). At high sustained CO_2 concentrations the changes in ocean chemistry will take thousands of years to be buffered by the natural dissolution of $CaCO_3$ from sediments and tens to hundreds of thousands of years to be eliminated completely by the weathering of rocks on land (Archer et al., 2009).

6.1.1.3. Hypoxia

The average dissolved oxygen concentration in the ocean is presently 162 µmol kg^{-1} (Sarmiento and Gruber, 2006). Concentrations range from over 500 µmol kg^{-1} in productive Antarctic waters super-saturated with oxygen (Carrillo et al., 2004) to zero in coastal sediments and in permanently anoxic deep layers of isolated water bodies, such as the Black Sea and the Cariaco Basin. Hypoxia results from oxygen depletion in excess of supply as in stratified water bodies (Section 6.1.1.2). Vast Oxygen Minimum Zones (OMZs) exist between less than 100 and more

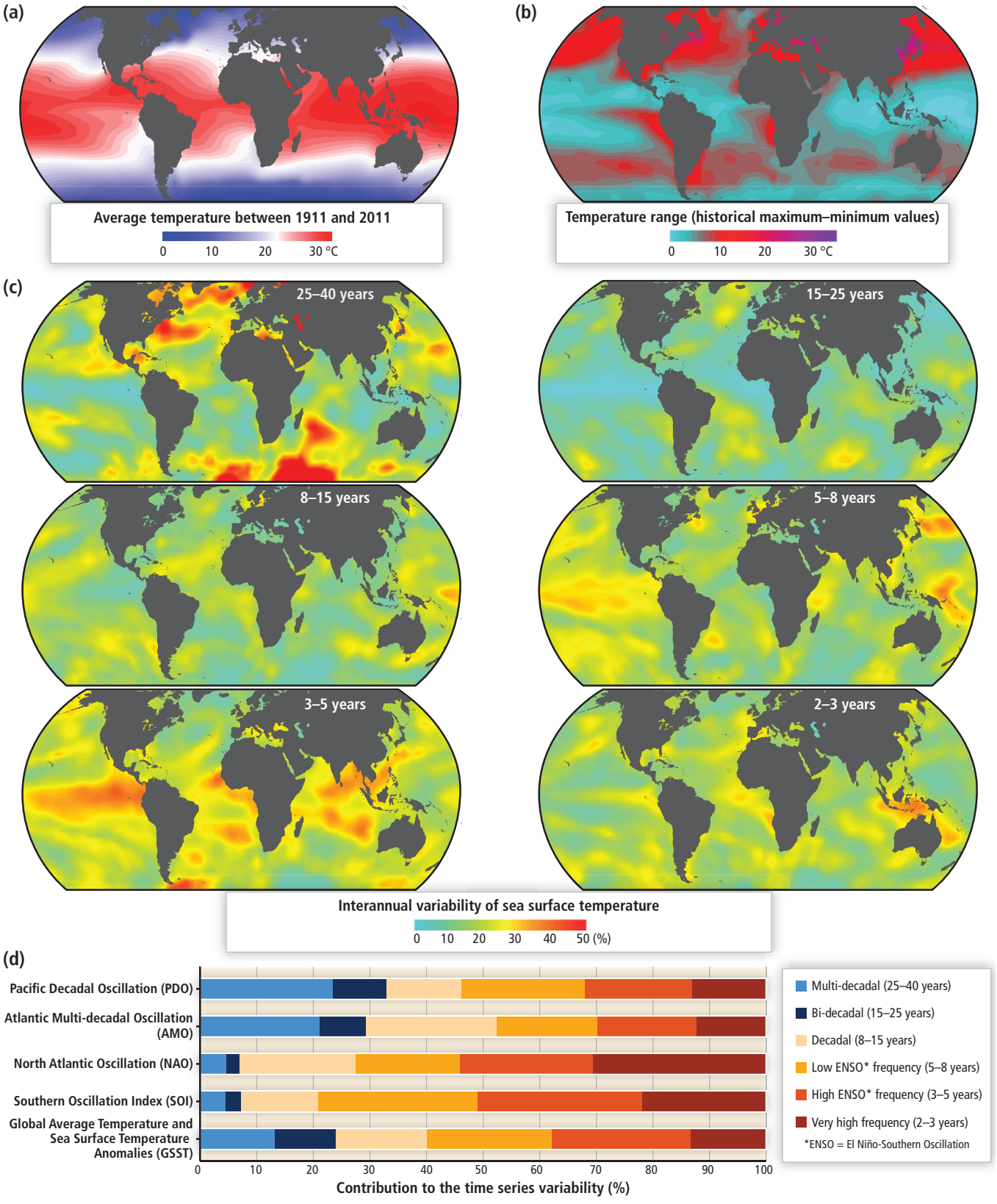


Figure 6-1 | Sea surface temperature variability between 1911 and 2011. (a) The sea surface temperature average for the period. (b) The temperature range calculated as the difference between the maximum and minimum values for each grid component during the century. (c) The spatial distribution of variability by time scales (based on the Extended Reynolds Sea Surface Temperature, NOAA, 2012) corresponds to the multi-decadal (25 to 40 years), bi-decadal (15 to 25 years), decadal (8 to 15 years), low ENSO (El Niño-Southern Oscillation) frequency (5 to 8 years), high ENSO frequency (3 to 5 years), and very high frequency (2 to 3 years) scales. The summed variabilities from the same 2°x2° box in all six maps corresponds to 100% of the time series variability. (d) The spectral density of some of the most widely used climate indices, accumulated in the same frequency windows. The total bar length (100%) corresponds to the cumulative variability of each time series between the 2 and 40 year frequency window. Climate indices were obtained from the NOAA ESRL Physical Sciences Division website.

than 900 m depths in Eastern Atlantic and Pacific tropical oceans. The ecological literature applies the term hypoxia (see Section 6.3.3) to O_2 concentrations below 60 µmol kg^{-1} (estimated at about 5% of global ocean volume; Deutsch et al., 2011). Pacific OMZs regularly reach oxygen levels below 20 µmol kg^{-1} (about 0.8% of global ocean volume; Paulmier and Ruiz-Pino, 2009), lower than Atlantic ones. Suboxic waters at <4.5 µmol O_2 kg^{-1} occupy about 0.03% of the ocean volume, mainly in the northeastern tropical Pacific (Karstensen et al., 2008).

OMZs are naturally present in many habitats including marine sediments, but are also expanding due to anthropogenic influences. Over the past 50 years, open ocean O_2 concentrations have decreased by a mean rate of 0.1 to >0.3 µmol kg^{-1} yr^{-1} (WGI AR5 Section 3.8.3; Stramma et al., 2008). In some OMZs the rate has been much higher due to warming, increased stratification, and rising biological O_2 demand (WGI AR5 Section 3.8.3). Long-term declines in O_2 by about 7 µmol kg^{-1} per decade have been documented at mid-water depths over much of the subarctic North Pacific (Keeling et al., 2010). In coastal regions, extremely hypoxic "dead zones" that exclude animal life, have increased from 42 reported in the 1960s to more than 400 in 2008 and been attributed to high oxygen demand from eutrophication, the local enrichment of nutrients, resulting in organic matter loading and its decay as well as nitrous oxide formation and release (Naqvi et al., 2000; Díaz and Rosenberg, 2008; Zhang et al., 2010).

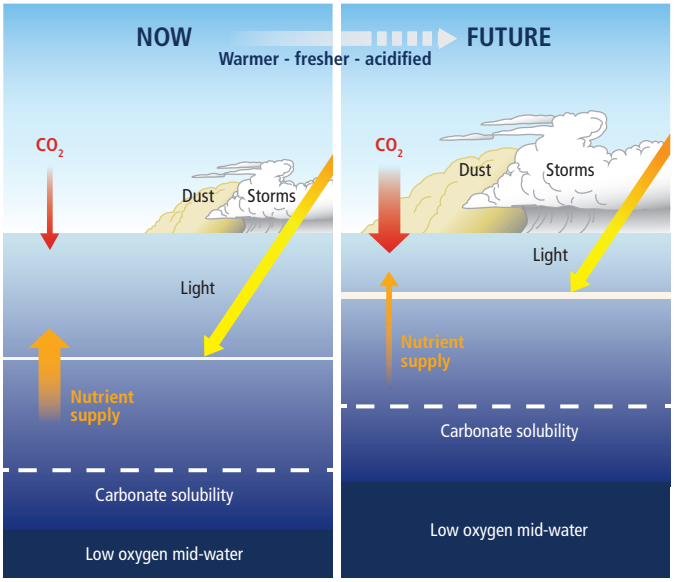


Figure 6-2 | Projected alteration (magnitude and frequency) of oceanic fluxes and atmospheric events due to a changing climate in the coming decades. Ocean properties will be altered from the sunlit surface layer to the mid-water stratum. In the surface ocean, the depth of the mixed layer (solid horizontal line) will shallow resulting in higher mean light levels. Increased density stratification (i.e., a strengthening sea water density gradient represented by the increasing thickness of the solid horizontal line) will reduce the vertical supply of nutrients for photosynthesizing organisms residing in the mixed layer. Anthropogenic CO_2 will acidify, that is, lower the pH of the surface ocean (note this happens in a pH range higher than 7 such that oceans will remain alkaline but less so due to acidification). The penetration of acidified waters to depth will result in a shallower depth (dashed horizontal line) at which $CaCO_3$ structures, such as shells, dissolve. At depth, the location of low-O_2 waters will progressively become shallower. In addition, changes in storm activity and dust deposition will influence ocean physics and chemistry, with consequent effects on ocean biota and hence ecosystems (courtesy of Reusch and Boyd, 2013).

Future warming will *likely* accelerate the spread of hypoxic zones, especially in temperate to sub-polar regions. Most models project decreasing global ocean oxygen contents by 1 to 7% from present-day concentrations in 2100 (Keeling et al., 2010; WGI AR5 Figure 6.30 under RCP8.5), with a mean decline by 3.4% in 2090 compared to the 1990s (Bopp et al., 2013). Warming and freshening of the surface layer will increase stratification and reduce the depth of winter mixing. The evolution of low O_2 zones will be linked to changes in fluvial runoffs (e.g. Milly et al., 2008; see also Section 5.3.4.3), the wind regime (e.g., Vecchi and Soden, 2007), as well as the intensity, duration, and seasonal timing of upwelling events (Snyder et al., 2003; see also Section 30.5.2). The potential contributions of destabilized methane hydrates and bacterial methane oxidation to exacerbate hypoxia and acidification at high latitudes remain to be explored (Westbrook et al., 2009). Currently, there is no consensus on the future volumes of hypoxic and suboxic waters because of large uncertainties in potential biogeochemical effects and in the evolution of tropical ocean dynamics due to both natural and anthropogenic causes (WGI AR5 Section 6.4.5). While volumes with O_2 concentrations <80 µmol kg^{-1} are projected to increase by several percent, suboxic waters <5 µmol O_2 kg^{-1} may undergo a 30% increase by 2100 compared to 2005 (*low confidence*; Bopp et al., 2013).

6.1.1.4. Light and Nutrients

Most models project that the mixed layer at the ocean surface (see Figure 6-2) will become shallower in the coming decades through a strengthening of the vertical density gradient (e.g., Sarmiento et al., 1998; Sallée et al., 2013). Mean light levels encountered by phytoplankton are set by incoming light from solar radiation, the depth of the mixed layer, and the degree to which underwater light is attenuated by living and non-living particles (Kirk, 1994). A shallower mixed layer will *likely* result in the resident phytoplankton receiving higher mean underwater light levels if the organisms are physically mixed through this stratum (Figure 6-2).

Enhanced, seasonally prolonged stratification (Holt et al., 2010), especially in the tropics, the North Atlantic, the Northeast Pacific, and the Arctic (Capotondi et al., 2012), will lead to decreased vertical transport of nutrients to surface waters (Doney, 2010; Figure 6-2). River plumes (Signorini et al., 1999), nutrient accumulation in the pycnocline as reported for North Pacific waters (Whitney, 2011), human-induced eutrophication, enhanced upwelling (Box CC-UP), and tidal mixing and estuarine circulation in coastal oceans could partly compensate for the projected reduction in nutrient supply in the oceans (*limited evidence*, *medium agreement*).

6.1.2. Historical and Paleo-Records

6.1.2.1. Historical Observations

Ocean ecosystems are variable in time and space, and in a non-steady-state, reflected in indices such as the North Atlantic Oscillation (NAO) Index, the Atlantic Multi-decadal Oscillation (AMO), the Arctic Climate Regime Index (ACRI), Pacific Decadal Oscillation (PDO), or the El Niño-Southern Oscillation (ENSO) (WGI AR5 Box 2.5; Figure 6-1; Section 30.5).

The combination of large, global data sets such as Reynolds, National Center for Atmospheric Research (NCAR), International Comprehensive Ocean-Atmosphere Data Set (ICOADS) with multi-decadal time series, for example, near Hawaii (HOT), Bermuda (BATS), the Ligurian Sea (DYFAMED), the Canaries (ESTOC), Kerguelen Island (KERFIX), Hokkaido Island (KNOT), and Taiwan (SEATS) has provided data on the physical and biogeochemical state of the oceans (Karl et al., 2003). These have been augmented by the limited-term, high-resolution programs World Ocean Circulation Experiment (WOCE) and Joint Global Ocean Flux Study (JGOFS).

Historical data sets provide baseline information on ecosystem states and document the responses of biota to both natural variability in the ocean system and surface ocean warming since the 1970s (Figure 6-3; Section 6.3.1). Such data sets are rare and regionally biased. Examples include changes in geographic ranges of plankton and seasonal timing (phenology) of different components of the ecosystem detected by the Continuous Plankton Recorder (CPR: e.g., Edwards et al., 2001; Richardson et al., 2006; Box 6-1) or multi-decadal shifts in pelagic ecosystems (CalCOFI) including higher parts of the food chain such as sardines and anchovies (Brinton and Townsend, 2003; Chavez et al., 2003; Lavaniegos and Ohman, 2003; see also Section 6.3.1) and the skeletal archives of long-lived organisms such as coralline algae (Halfar et al., 2011), bivalves (Schöne et al., 2003), and corals (De'ath et al., 2009).

Systematic, long-term interdisciplinary observations using repeated, highly calibrated measurements at a given field site are required to capture high- and low-frequency events, for example, regime shifts (abrupt changes between contrasting, persistent states of any complex system; deYoung et al., 2008). Direct observations are complemented by satellite remotely sensed data sets. Ocean color data (e.g., Coastal Zone Color Scanner (1978–1986), Sea-Viewing Wide Field-of-View Sensor (SeaWiFS, 1997–2010), and Moderate Resolution Imaging Spectroradiometer (MODIS-AQUA, 2002 to the present); McClain, 2009) provide estimates of chlorophyll concentrations (a proxy for phytoplankton stocks and net primary production (NPP); Sections 6.2.1, 6.3.4; Saba et al., 2011). Total chlorophyll cannot be measured from space; therefore, the near-surface value (approximately one optical depth) is extrapolated to whole water-column chlorophyll based on vertical distribution using region-specific algorithms. Large uncertainties persist, as these estimates reflect both phytoplankton stocks and their physiological status (Dierssen, 2010; Behrenfeld, 2011). The approximately 15-year archived time series of SeaWiFS is too short to reveal trends over time and their causes. It is an example for the general issue that undersampling of ocean phenomena in time and space limits our current ability to assess present states, to distinguish effects of anthropogenic change from natural variability, and to project future changes (Henson et al., 2010; Beaulieu et al., 2013; Box CC-PP).

6.1.2.2. Paleontological Records

Paleontological records in marine sediments provide long-term, low-resolution data on the spatial distributions of organisms and their abundances from all ages and latitudes. This information can be readily related to the concurrent shifts in multiple environmental properties that are also recorded in these sediments. The records provide insights into shifts, expansions, and contractions of biogeographic ranges; species extinctions and emergences; and changes in species abundance, as well as the environmental forcings to which organisms respond. Temporal trends reveal influences of temperature, hypoxia, CO_2, and food availability on organisms and ecosystems (Section 6.1.1; Figure 6-3).

Owing to insufficient resolution, the geological record often does not allow the direct attribution of a biological change to a single driver or the identification of various drivers and their relative importance. Support for projections of future changes in present-day ecosystems and their services is thus limited (*low confidence*; Sections 6.4, 6.5). Nonetheless, information gained from the geological record is invaluable, as both paleo and present climatic shifts share the same combination and sign of environmental changes: increasing atmospheric CO_2 causing warming and CO_2 enrichment in the surface ocean, leading to enhanced stratification of the upper ocean and a decrease in dissolved O_2 (WGI AR5 Chapter 3; Section 5.3). A combination of models (WGI AR5 Chapters 3, 6, 12) and geological data can be used to forecast future impacts on ocean biota (*medium confidence*).

The last glacial-interglacial transition is associated with an average increase in atmospheric CO_2 of approximately 1 µatm per century between 18 and 10 thousand years before present (kyr BP) (WGI AR5 Chapter 5), a significantly slower increase than the approximately 90 µatm in the last century (WGI AR5 Chapters 5, 6). Consequently, the average pH change of 0.002 pH units per century during the glacial-interglacial transition is small relative to the ongoing anthropogenic perturbation of >0.1 pH unit per century (WGI AR5 Section 3.8.2). Overall the upper glacial ocean was more O_2-rich than today's ocean (Jaccard and Galbraith, 2012) and between 0.7°C and 2.7°C colder, with strong regional differences of up to 10°C cooling in the North Atlantic and 2 to 6°C in the Southern Ocean (WGI AR5 Chapter 5, Table 5.2). During warming from the glacial into the interglacial marine plankton such as foraminifera, coccolithophores, diatoms, dinoflagellates, and radiolarians showed marked poleward range expansion (*high confidence*; see WGI AR5 Section 5.7; CLIMAP Project Members, 1976; MARGO Project Members, 2009). Under the lower glacial CO_2 concentrations, calcification in planktonic foraminifera was higher (*limited evidence*, *medium agreement*).

The most prominent abrupt climate change periods in the recent geological record, developing within 10 to 100 years, are associated with Dansgaard-Oeschger (DO) and Heinrich events (WGI AR5 Section 5.7), which occurred repetitively during the last 120 kyr. Whereas the atmospheric changes happened within a few decades, the sea surface temperature in the North Atlantic changed by up to 5°C within decades to centuries (WGI AR5 Section 5.7). Southern Ocean temperature changes were slower (hundreds to thousands of years; Barker et al., 2009). The cold phase of a DO event led to the migration of polar foraminiferal species toward the equator, in the North Atlantic as far south as the Iberian Peninsula (Martrat et al., 2004). Abrupt (approximately 100-year) abundance changes in the Southern Ocean were associated with latitudinal shifts in the Antarctic Circumpolar Current and associated species (Barker et al., 2009) akin to modern changes in plankton range due to warming (Box CC-MB, Box 6-1). During the DO warm phases the Monsoon-driven Arabian Sea upwelling records show enhanced primary

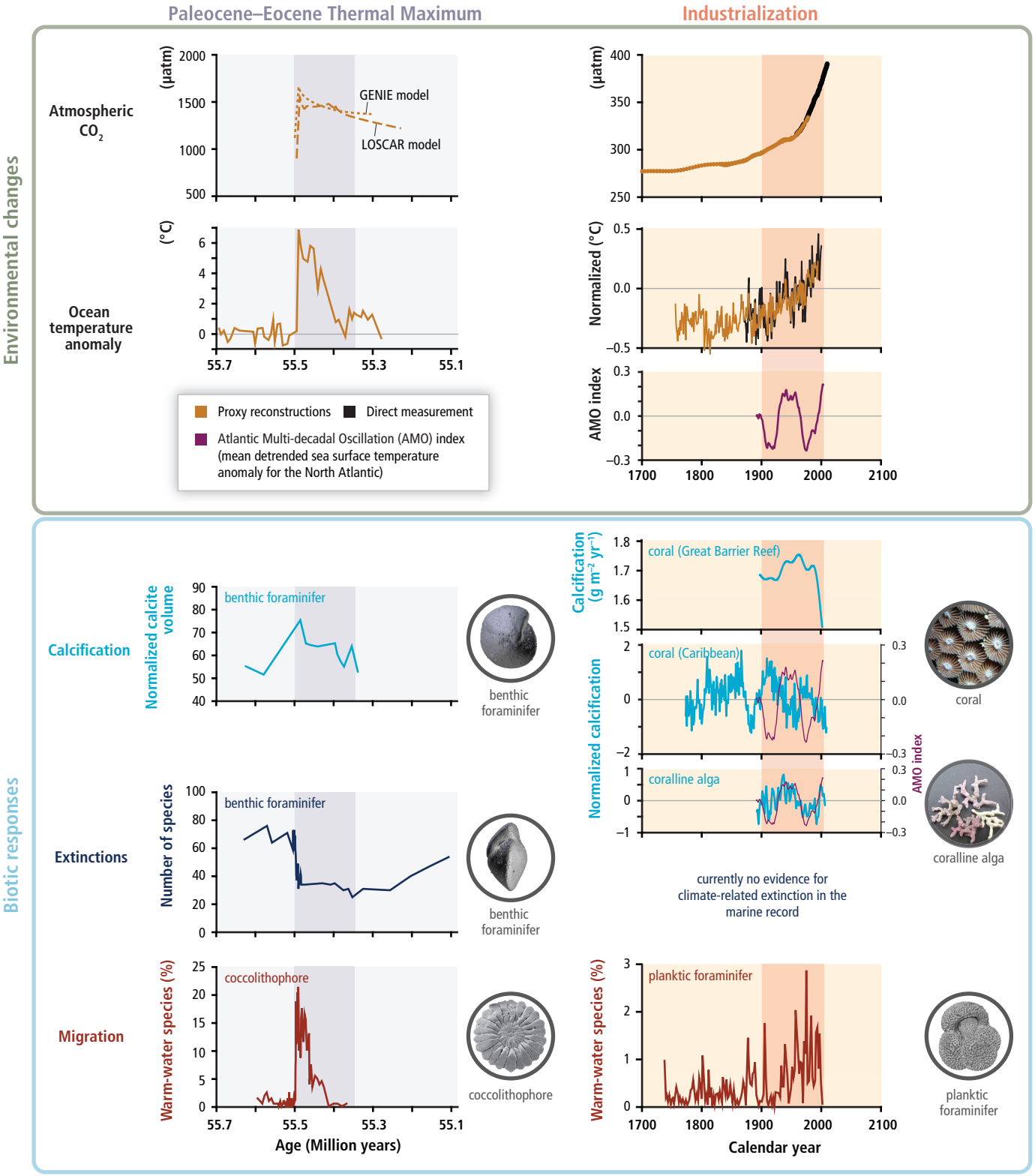


Figure 6-3 | Environmental changes (top) and associated biological responses (bottom) for the Paleocene–Eocene Thermal Maximum (PETM, left) and the industrial era (right). The PETM represents the best geological analog for the future ocean because of its rapid environmental change. Episodes of largest environmental change are indicated with darker bands. Note the different time scale between the two columns. Both time intervals are characterized by rapid warming both on land and in the ocean (modern: Wilson et al., 2006 and PETM: Kennett and Stott, 1991) and increases in CO_2 (modern: Etheridge et al. 1996; Keeling et al., 2005 and PETM: Zeebe et al., 2009 (LOSCAR model); Ridgwell and Schmidt, 2010 (Grid Enabled Integrated Earth System Model (GENIE model))). For the recent industrial era, the Atlantic Multi-decadal Oscillation (AMO; see Figure 6-1 and Section 6.1.2.1) is shown to highlight an example of high-frequency sea surface temperature fluctuations (Enfield et al., 2001) and their influence on marine biota. Note the species-specific calcification responses to climate change with decreases, increases, and high variability (coralline alga: Halfar et al., 2011; coral: Vásquez-Bedoya et al., 2012; De'ath et al., 2013; PETM: Foster et al., 2013). While there was extinction during the PETM (Thomas, 2003), there is currently no evidence for climate-related extinction in the marine record. Warming led to migration of warm-water species into previous cold-water habitats (modern: Field et al., 2006; PETM: Bralower, 2002). Pictures are examples of organisms highlighting the processes in each panel, and are not to scale.

and export production, reduced oxygenation, and denitrification, all within approximately 200 years (Higginson et al., 2004).

The last time the atmospheric CO_2 content approached that of today was during the Pliocene warm period (3.3 to 3.0 million years ago (Ma)), with long periods of atmospheric CO_2 levels between 330 and 400 µatm (Pagani et al., 2010; Seki et al., 2010) and equilibrated temperatures approximately 2°C warmer than today (*medium confidence*; Haywood et al., 2009; WGI AR5 Chapter 5). The Mid-Pliocene Warm Period saw a poleward expansion of tropical planktonic foraminifera (*high confidence*; Dowsett, 2007). Coccolithophores (Bown et al., 2004), corals (Jackson and Johnson, 2000), and mollusks (Vermeij and Petuch, 1986) remained unaffected with respect to rates of species extinction or emergences compared to background rates.

Perhaps the best analog for the future ocean is the Paleocene-Eocene Thermal Maximum (PETM, 55.3 Ma). The PETM was an event of warming (Dunkley Jones et al., 2013), and ocean acidification (Zachos et al., 2005) over millennia (Cui et al., 2011; Stassen et al., 2012) with increased runoff and nutrients into the shelf ecosystems. Model simulations for the PETM show 10 times lower rates of CO_2 input and hence ocean acidification compared to today (*medium confidence*; Ridgwell and Schmidt, 2010). Depending on the assumed rate and magnitude of the CO_2 release, models project pH declined by 0.25 to 0.45 units in PETM surface waters and a reduction in surface ocean aragonite saturation from $\Omega = 3$ to $\Omega = 2$ or even as low as 1.5 (Ridgwell and Schmidt, 2010). Warming caused range expansions of warm-water taxa toward higher latitudes (*high confidence*). The composition of plankton assemblages changed both within and between phytoplankton groups (Gibbs et al., 2006; Sluijs and Brinkhuis, 2009), possibly reflecting the warming trend and/or changes in nutrient availability (Sections 6.2.2-3). There was no bias in extinction toward more heavily calcifying species, possibly as slow CO_2 input led to minor surface water acidification. By contrast, benthic foraminifera, the dominant deep water eukaryote, recorded up to 50% extinction (Thomas, 2007). In contrast to sediment dwellers, more mobile pelagic crustaceans (ostracods) did not show any significant change in species composition (Webb et al., 2009). In shallow coastal waters, calcareous algae and corals were replaced by symbiont-bearing benthic foraminifera (*medium confidence*; Scheibner and Speijer, 2008).

The warm climates of the Mesozoic (251 to 65 Ma) led to a number of anoxic events in the oceans (Jenkyns, 2010). In some cases, OMZs expanded vertically, leading to anoxia in upper water layers (Pancost et al., 2004). Some of the Cretaceous oceanic anoxic events were associated with extinctions or increased species turnover (normalized sum of originations and extinctions) of planktonic foraminifera and radiolarians (30%). Such turnover was very small in other groups of organisms (e.g., a maximum of 7% of coccolithophores; Leckie et al., 2002). The attribution of these evolutionary changes to reduced O_2 is tenuous as warming, changes in nutrient supply, and possibly ocean acidification occurred concomitantly (Hönisch et al., 2012).

Global-scale collapse of marine ecosystems is rare, even in the geological record. Some mass extinctions, in particular the Permian Period extinction 251 Ma, have been associated with large-scale inputs of carbon into the atmosphere and ocean, with associated warming and deep-sea O_2 decline (Knoll et al., 2007; Kiessling and Simpson, 2011). The end-Permian mass extinction preferentially affected reef organisms such as corals and sponges resulting in a 4 Myr period without reef builders (Kiessling and Simpson, 2011), and underscores that vulnerabilities differ among organisms depending on anatomy, physiology, and ecology (Knoll and Fischer, 2011). The rates of environmental change and any potential acidification have not yet been accurately constrained for these events.

Of the last 100 Myr, only the last 2 Myr had CO_2 levels of approximately 190 to 280 ppm, comparable to preindustrial values. Values like those predicted for the mid and end of this century can solely be found in the geological record older than 33 Ma, with large uncertainties in the absolute numbers (WGI AR5 Section 5.3; Hönisch et al., 2012). That marine biota thrived throughout high CO_2 times cannot imply that marine organisms will remain unaffected in a future warm, high-CO_2 world. The key environmental issue of the 21st century is one of an unprecedented rate of change, not simply magnitude, of CO_2 levels (Hönisch et al., 2012). The current rate and magnitude of ocean acidification are at least 10 times faster than any event within the last 65 Ma (*high confidence*; Ridgwell and Schmidt, 2010) or even 300 Ma of Earth history (*medium confidence*; Hönisch et al., 2012). The slower events in geological history provide *robust evidence* (*high agreement*) for environmentally mediated changes in biogeographic ranges of fauna and flora, their compositional changes, extinctions, and, to much lesser degree, emergences (*very high confidence*). No past climate change event perfectly parallels future projections of anthropogenic climate change, which is unprecedented in evolutionary history. Existing similarities indicate, however, that future challenges (Sections 6.1.1, 6.3.1-8) may be outside the adaptive capacity of many organisms living in today's oceans (*low* to *medium confidence*).

6.2. Diversity of Ocean Ecosystems and Their Sensitivities to Climate Change

Global-scale observation and modeling studies provide *robust evidence* of present and future climate-mediated alterations of the ocean environment (*high agreement*; Section 6.1.1; WGI AR5 Chapters 3, 6; Bopp et al., 2013), which in turn impact ocean ecosystems (*high confidence*; Boyd and Doney, 2002; Drinkwater et al., 2010; Hoegh-Guldberg and Bruno, 2010). An assessment of present findings and projections requires knowledge of the characteristics of ocean biota and ecosystems and their climate sensitivity.

Life on Earth is diverse as a result of nearly 4 billion years of evolutionary history. Marine microorganisms are the oldest forms of life and the most functionally diverse; multicellular organisms are constrained to limited functional abilities. Knowledge of overarching similarities across the organism domains Archaea, Bacteria, and Eukarya (Woese et al., 1990) or kingdoms Bacteria, Protozoa, Fungi, Plantae, Animalia, and Chromista (Cavalier-Smith, 2004) would facilitate projections of climate impacts. The phylogenetic and metabolic diversity of microbes (i.e., viruses, archaea, bacteria, protists, and microalgae) sustains key ecosystem processes such as primary production, CO_2 fixation and O_2 production, the conversion of nitrogen into ammonia (N_2 fixation), and the use of nitrate, sulfate, CO_2, and metals (iron and manganese) in metabolism instead of O_2 when it is absent. Microbes enhance the horizontal

transfer of genetic information between unrelated individuals, thereby enhancing biodiversity (McDaniel et al., 2010). Microbes may respond to climate change by exploiting their large diversity, undergoing species replacements (Karl et al., 2001), and thereby sustain their biogeochemical roles. Species replacements also occur among plants and animals, but in most cases research has focused on their resilience, well-being, abundance, survival, and conservation under climate change (FAQ 6.2).

6.2.1. Pelagic Biomes and Ecosystems

Pelagic organisms are key to biogeochemical processes in the ocean. The base of the marine food web is the photosynthetic fixation of CO_2 by phytoplankton, a process termed (net) primary production (NPP; Box CC-PP). Photosynthesis is controlled by light, temperature, inorganic nutrients (CO_2, nitrate, phosphate, silicate, and trace elements including iron), and the density-dependent stability of the surface mixed-layer depth (MLD) (Section 6.1.1; Figure 6-2; Sverdrup, 1953; González-Taboada and Anadón, 2012). Environmental variability and the displacement of organisms by ocean currents cause variability in phytoplankton productivity, competitiveness, and natural selection (Margalef, 1978) and result in changes in carbon sequestration (Box CC-PP; Figure 6-4). Nutrient limitation leads to a decrease in NPP or chlorophyll levels and a reduction in the amount of energy supplied to higher trophic levels, including fish and invertebrates (*high confidence*; Ware and Thomson, 2005; Brander, 2007), affecting fishery yields (Cheung et al., 2008; Friedland et al., 2012). The wide range of trophic structures in marine food webs and the potentially nonlinear changes in energy transfer under different NPP and temperature scenarios (Stock and Dunne, 2010) hamper accurate projections of changes in higher trophic levels.

6.2.2. Benthic Habitats and Ecosystems

The ocean's primary production is inextricably linked with benthic (sea floor) communities via the biological pump (Figure 6-4), the chemical exchange of nutrients and gases, and the existence of organisms with both pelagic and benthic life history stages. Even in abyssal habitats, a continuous rain of organic detritus serves as the primary source of carbon and energy. Therefore climate impacts on surface marine ecosystems will impact even the deepest benthic communities, even if direct changes to their physical habitat do not occur (Smith et al., 2009).

Benthic organisms living in shallow waters or the intertidal zone (where they encounter temporary exposure to air) are exposed to widely fluctuating and progressively changing means and extremes of environmental variables, such as temperature, oxygen, CO_2, salinity, and sea level (WGI AR5 Chapters 3, 13; Sections 6.3.1-3, 6.3.5). Plants and sessile or slow moving animals may be unable to escape from unfavorable changes except by means of advection of fertilized eggs or planktonic larvae. If climate change harms those species engineering benthic habitats, the entire ecosystem may be impacted. This concerns those ecosystem engineers, which form habitat from the structures they produce (e.g., corals forming skeletons; Section 6.3.1) and those forming habitat through their behavior (e.g., worms reworking and irrigating sediment in a process termed bioturbation). Effects on both types of ecosystem engineers (Sections 6.3.1-8) influence the regeneration of nutrients and affect benthic-pelagic coupling.

6.3. Climate Change Impacts from Organism to Ecosystem

Understanding climate-induced alterations in the functioning of individual organisms, species populations, communities (assemblages of various species), and ecosystems builds on studies in the laboratory, in micro- and mesocosms (closed small- to medium-sized experimental systems approximating natural conditions, holding selected biological communities), and of biota or communities in the field as well as modeling. These data inform us which taxonomic groups in what regions are more susceptible to climate change (Boyd et al., 2011). Empirical studies of marine organism and ecosystem sensitivities have begun identifying the mechanisms and processes linking climate to ecosystem changes (Drinkwater et al., 2010; Ottersen et al., 2010). Changes in ecological community composition, species interactions, and food web dynamics often build on organismal effects elicited by climate forcing (e.g., Section 6.3.1.5; Boyd et al., 2010; Ottersen et al., 2010). The underlying mechanisms respond to climate-related factors in a hierarchy from organism (highest), tissue, cell to molecular (lowest)

Table 6-1 | To assess how a changing climate will alter the ocean's biological pump (Figure 6-4) and determine the resulting biogeochemical feedbacks on global climate, changes in a wide range of processes from cells to ocean basins, and from epipelagic to mesopelagic, must be quantified. This table illustrates the complexity of the integrated knowledge platform needed to provide evidence of these biogeochemical ramifications and thus the present limits to clear conclusions about climate-induced effects on the biological pump (NPP = net primary production; C = carbon; TEP = transparent exopolymer particle; DOM = dissolved organic matter; POM = particulate organic matter).

Alteration of physiological rates	Biogeographical changes/ community shifts	Altered foodweb structure: trophodynamics	Changes to particle dynamics	Biogeochemical changes/ climatic feedbacks
• NPP (Bopp et al., 2002, 2013) • Particle solubilization through bacterial ectoenzymes (Christian and Karl, 1995) • TEP production (Engel et al., 2004) • Microzooplankton grazing rates (Rose et al., 2009)	• Microbial community structure (Giovannoni and Vergin, 2012) • Phytoplankton community structure, e.g., biomes (Boyd and Doney, 2002) • Alteration of zooplankton biomes (Beaugrand et al., 2009) • Faunistic shifts at depth (Jackson and Burd, 2001)	• Altered prey-predator linkages (Lewandowska and Sommer, 2010)	• Faecal pellet geometry (Wilson et al., 2008) • C partitioning between DOM vs. POM, e.g., TEP (Riebesell et al., 2007) • Sinking rates/seawater viscosity (Lam and Bishop, 2008) • Ballasting, e.g., calcite versus opal (Klaas and Archer, 2002)	• Particle flux/C sequestration (Bopp et al., 2002) • Shifts in elemental stoichiometry of planktonic communities (Karl et al., 2003) • Remineralization rate; $[O_2]$, hypoxia; nutrient resupply (Gruber, 2011) • Activity of the microbial loop; vertical carbon export (Grossart et al., 2006; Piontek et al., 2010)

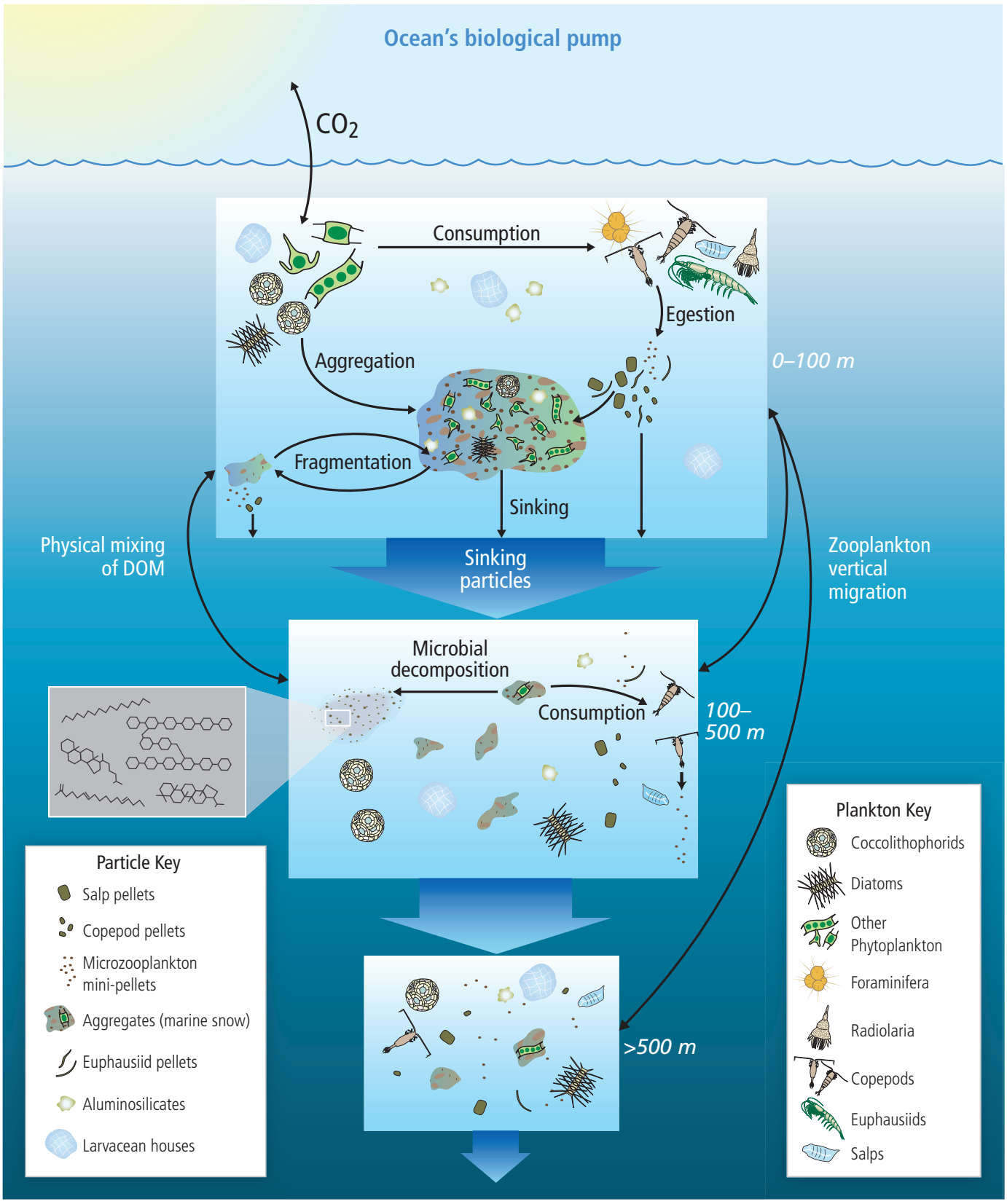


Figure 6-4 | A schematic representation of the ocean's biological pump, which will be influenced by climate change and is a conduit for carbon sequestration. It is difficult to project how the pump might be altered and whether it would represent a positive or negative feedback to climate change through the cumulative effects of affected processes, surface to depth (Table 6-1): shifts in net primary production, floristic and faunistic community composition in the pelagic realm, and in grazing rates; alterations to the ballasting of settling particles and the proportion of net primary production released as dissolved organic matter; modified bacterial enzymatic rates and particle solubilization; faunistic shifts at depth. Note that the relative sizes of the organisms, particles, and particle building blocks are not presented to scale (modified from Buesseler et al. (2008) by J. Cook / WHOI).

Frequently Asked Questions

FAQ 6.2 | What is different about the effects of climate change on the oceans compared to the land, and can we predict the consequences?

The ocean environment is unique in many ways. It offers large-scale aquatic habitats, diverse bottom topography, and a rich diversity of species and ecosystems in water in various climate zones that are found nowhere else.

One of the major differences in terms of the effect of climate change on the oceans compared to land is ocean acidification. Anthropogenic CO_2 enters the ocean and chemical reactions turn some of it to carbonic acid, which acidifies the water. This mirrors what is also happening inside organisms once they take up the additional CO_2. Marine species that are dependent on calcium carbonate ($CaCO_3$), such as shellfish, seastars, and corals, may find it difficult to build their shells and skeletons under ocean acidification. In general, animals living and breathing in water like fish, squid, and mussels have between five and 20 times less CO_2 in their blood than terrestrial animals, so CO_2-enriched water will affect them in different and potentially more dramatic ways than species that breathe in air.

Consider also the unique impacts of climate change on ocean dynamics. The ocean has layers of warmer and colder water, saltier or less saline water, and hence less or more dense water. Warming of the ocean and the addition of more freshwater at the surface through ice melt and higher precipitation increases the formation of more stable layers stratified by density, which leads to less mixing of the deeper, denser, and colder nutrient-rich layers with the less dense nutrient-limited layers near the surface. With less mixing, respiration by organisms in the mid-water layers of stratified oceans will produce oxygen-poor waters, so-called oxygen minimum zones (OMZs). Large, more active fish can't live in these oxygen poor waters, while more simple specialized organisms with a lower need for oxygen will remain, and even thrive in the absence of predation from larger species. Therefore, the community of species living in hypoxic areas will shift.

State-of-the-art ecosystem models build on empirical observations of past climate changes and enable development of estimates of how ocean life may react in the future. One such projection is a large shift in the distribution of commercially important fish species to higher latitudes and reduced harvesting potential in their original areas. But producing detailed projections, for example, what species and how far they will shift, is challenging because of the number and complexity of interactive feedbacks that are involved. At the moment, the uncertainties in modeling and complexities of the ocean system even prevent any quantification of how much of the present changes in the oceans are being caused by anthropogenic climate change or natural climate variability, and how much by other human activities such as fishing, pollution, etc.

It is known, however, that the resilience of marine ecosystems to adjust to climate change impacts is *likely* to be reduced by both the range of factors and their rate of change. The current rate of environmental change is much faster than most climate changes in the Earth's history, so predictions from longer term geological records may not be applicable if the changes occur within a few generations of a species. A species that had more time to adapt in the past may simply not have time to adapt under future climate change.

levels of biological organization (Pörtner, 2002a; Pörtner and Knust, 2007; Raven et al., 2012). Such knowledge aids the interpretation and attribution to climate change of observed effects and is a major asset for projections of future impacts.

The genetic and physiological underpinning of climate sensitivity of organisms sets the boundaries for ecosystem response and provides crucial information on sensitivities, resilience, and the direction and scope of future change. As anthropogenic climate change accelerates, a key issue is whether and how quickly organisms can compensate for effects of individual or multiple drivers, by short-term acclimatization or long-term evolutionary adaptation across generations. Evolutionary adaptation depends on the genetic variation within a population, from which the environment selects the fittest genotypes (Rando and Verstrepen, 2007; Reusch and Wood, 2007). Genetic variation depends on mutation rates, generation time, and population size (Bowler et al., 2010). However, epigenetic mechanisms, such as modifications of the genome by DNA methylation, can also influence fitness and adaptation (Richards, 2006) and can be remarkably rapid as seen in terrestrial ecosystems (Bossdorf et al., 2008). In plants and animals the rate of evolutionary adaptation is constrained by long generation times, but enhanced by high phenotypic variability and high mortality rates among early life stages as a selection pool (e.g., Sunday et al., 2011). The limits to acclimatization or adaptation capacity are presently unknown.

However, mass extinctions occurring during much slower rates of climate change in Earth history (Section 6.1.2) suggest that evolutionary rates in some organisms may not be fast enough to cope.

Comprehensive understanding of climate change effects on ecosystems requires addressing the effects of individual drivers across organism taxa (Sections 6.3.1-4), the integrated action of multiple drivers (Section 6.3.5), the consequences for food webs (Section 6.3.6), and the specific effects on animals breathing in air (Section 6.3.7) and operating at the highest trophic levels.

6.3.1. Temperature Effects

The effects of temperature on ecosystems largely result from organismal responses. This requires that information on organisms' thermal sensitivities, limits, and functional properties is used to assess how temperature changes have affected and will continue to affect species distributions, abundances, diversity, trophic interactions, community assemblages, risks of species extinctions, and ecosystem functioning. Organisms also respond to temperature-driven changes in the physical environment such as stratification, reduced sea ice cover, and freshening. Ambient temperature interacts with other drivers such as ocean acidification and hypoxia (Section 6.3.5). Ambient temperature plays a more limited role for marine mammals and seabirds (Section 6.3.7).

6.3.1.1. Principles

All organisms including marine ones have limited temperature ranges within which they live and function. Organismal performance is related to temperature by curves called thermal reaction norms (Figure 6-5), which *likely* apply across all organisms (Chevin et al., 2010), from viruses (Knies et al., 2006), bacteria (Ratkowsky et al., 1983), and phytoplankton (Eppley, 1972; Thomas et al., 2012) to macroalgae and plants (Bolton and Lüning, 1982; Müller et al., 2009; Vitasse et al., 2010) and animals (Huey and Kingsolver, 1989; Angilletta, 2009). Heat tolerance thresholds differ greatly between organisms and are hypothesized to be lowered by rising organizational complexity and body size (Pörtner, 2002a,b). Maximum heat limits of animals and plants are close to the maximum

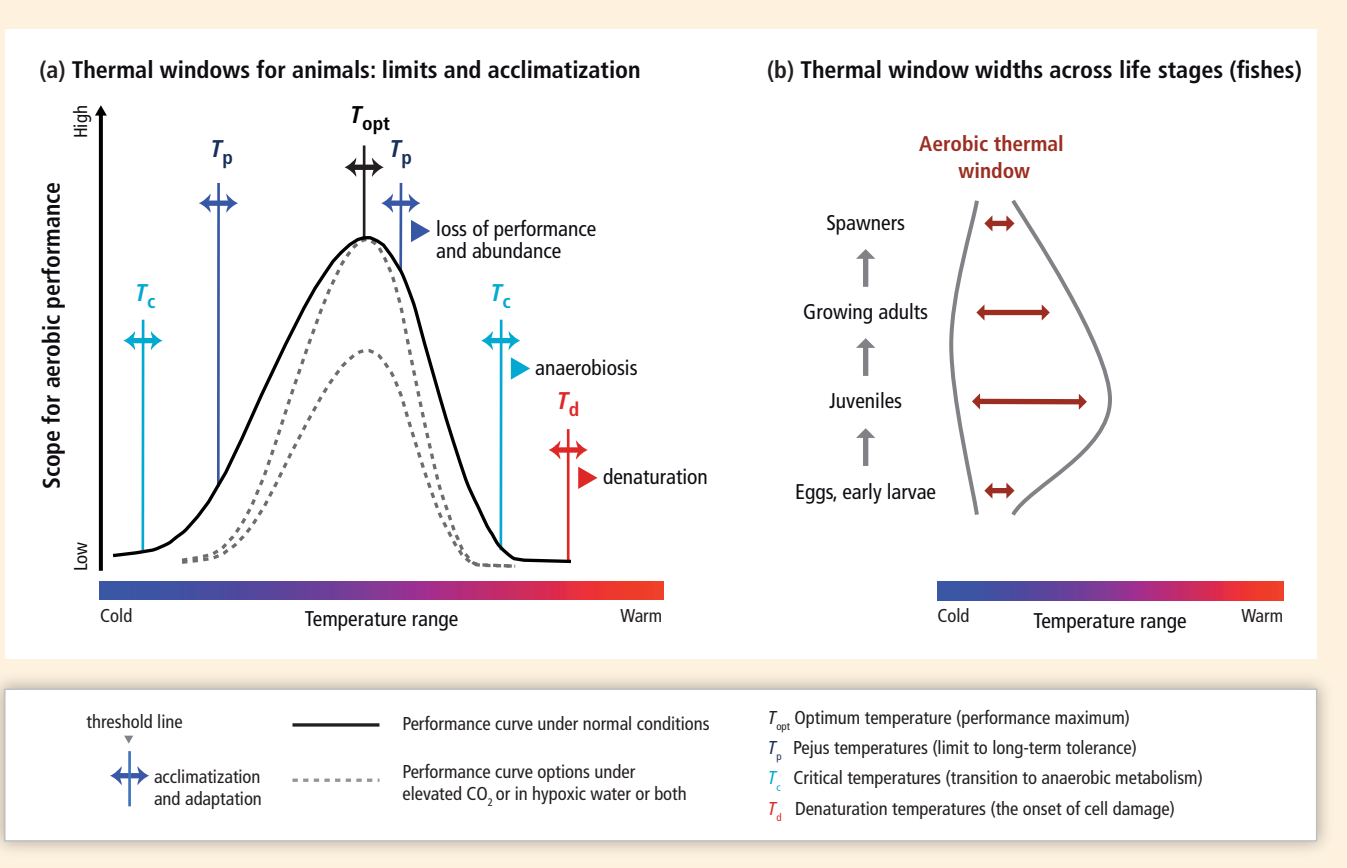


Figure 6-5 | Thermal specialization of an organism explains the why, how, when, and where of climate sensitivity. (a) The thermal tolerance range and performance levels of an organism are described by its performance curve (exemplified for an animal). Each performance (e.g., exercise, growth, reproduction) is maximal at its optimum temperature (T_{opt}), and becomes progressively constrained during cooling or warming. Surpassing the first low- and high-temperature thresholds (T_p; p, pejus: getting worse) means going into time-limited tolerance. Once further cooling or warming surpasses the next low or high thresholds (T_c; c, critical), oxygen availability becomes insufficient and an anaerobic metabolism begins. Denaturation temperatures (T_d) are even more extreme and characterized by the onset of damage to cells and proteins. Horizontal arrows indicate that T_p, T_c, and T_d thresholds of an individual can shift, within limits, between summer and winter (seasonal acclimatization) or when the species adapts to a cooler or warmer climate over generations (evolutionary adaptation). Under elevated CO_2 levels (ocean acidification) and in hypoxic waters performance levels can decrease and thermal windows narrow (dashed gray curves). (b) The width of the thermal range (horizontal arrows) also changes over time when an individual develops from egg to larva to adult and gains weight and size. Blue to red color gradients illustrate the range between cold and warm temperatures (after Pörtner, 2002a, 2012; Pörtner and Farrell, 2008).

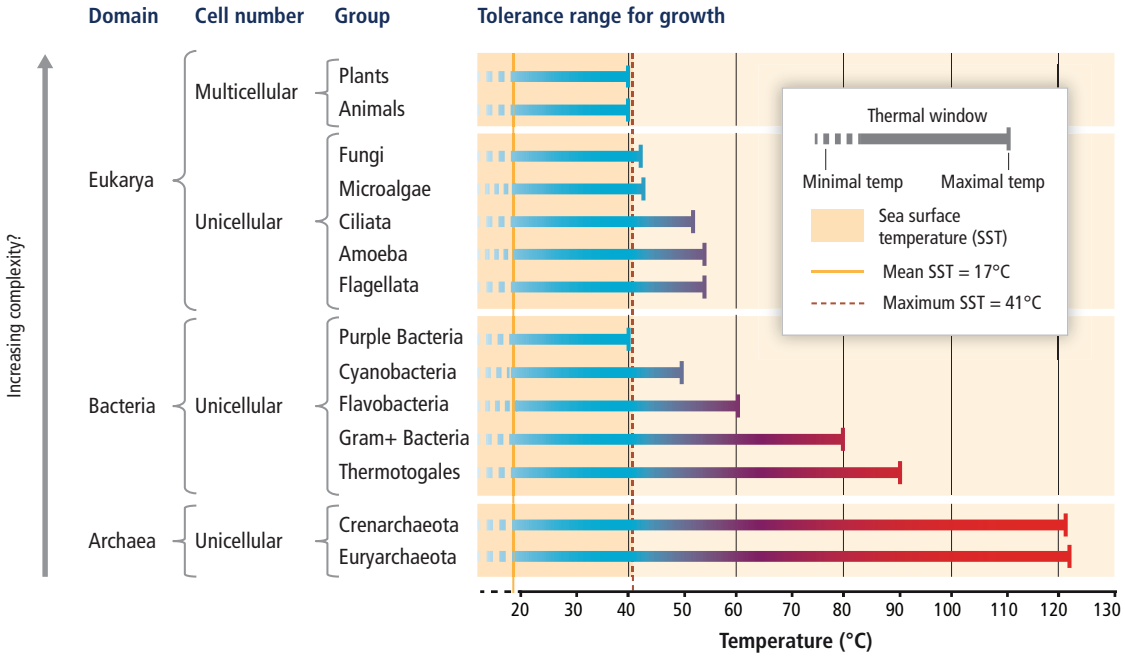


Figure 6-6 | Maximal values of temperature covered by various domains and groups of free-living marine organisms (bacteria to animals; domains and groups modified after Woese et al., 1990). High organizational complexity is hypothesized to be associated with decreasing tolerance to heat and to enable an increase in body size which in turn, decreases heat tolerance further (Sorokin and Kraus, 1962; Chevaldonné et al., 2000; Alker et al., 2001; Baumgartner et al., 2002; Pörtner, 2002a,b; Campbell et al., 2006; De Jonckheere et al., 2009, 2011). In the domain Bacteria, the Thermotogales are less complex and most tolerant to high temperatures (Huber et al., 1986; Tenreiro et al., 1997; Takai et al., 1999; Ventura et al., 2000; Abed et al., 2002). The highest temperature at which growth can occur is 122°C for hydrothermal vent archaea, seen under elevated hydrostatic pressure in laboratory experiments (Kashefi and Lovley, 2003; Takai et al., 2008).

temperature found in the warmest oceans (Figure 6-6). Knowledge of reaction norms, thermal limits, and underlying mechanisms is most advanced in animals (Pörtner et al., 2012; see also Section 6.3.1.4). Their role in underpinning biogeography has not been explored systematically in other organisms (e.g., Green et al., 2008), reducing the confidence level in assessments of thermal impacts. In animals, changes in physiological performances influence growth, body size, behavior, immune defense, feeding, reproductive success, biogeography, phenology, and therefore ecosystem structure and functioning. Shape and width of the curves can shift through acclimatization and evolutionary adaptation (Figure 6-5a) and during life history (Figure 6-5b), with implications for the distribution boundaries of species or populations (Section 6.3.1.5).

For any species, tracking the climate-induced displacement of tolerated ambient temperatures by undergoing shifts in biogeographical ranges to, e.g., higher latitudes during warming (Section 6.3.1.5; Figure 6-7) can be understood as a simple mode of adaptation, implemented through dispersal (e.g., of pelagic life stages), active movements (e.g., of migrating adult fishes), or passive displacement (e.g., of early life stages or plankton with drifting water masses). Conversely, fully completed acclimatization or evolutionary adaptation (Figure 6-5) would involve shifting thermal tolerance ranges and allow species to resist the temperature trend (e.g., warming) and to sustain fitness in their previous habitat.

6.3.1.2. Microbes

Temperature effects on growth, abundance, distribution, phenology, and community structure of highly diverse microbes have large implications for ecosystem functioning (Section 6.3; Box CC-PP). A warming ocean may initially enhance the metabolic rates of microbes (Banse, 1991) and stimulate their overall growth (Bissinger et al., 2008). Data from the Continuous Plankton Recorder (Section 6.1.2) in the Northeast Atlantic confirm that warming from 1960 to 1995 enhanced phytoplankton growth (Edwards et al., 2001). Eventually, with warming, the thermal tolerance of some groups will be challenged (Chevin et al., 2010), leading to the replacement of species. This is reflected in increasing fractions of smaller phytoplankton in warmer relative to colder waters (Morán et al., 2010; Flombaum et al., 2013).

In response to transient warming, phytoplankton distribution in the North Atlantic shifted poleward by hundreds of kilometers per decade since the 1950s. Phenology of plankton in the North Atlantic was also affected, with differences in sensitivity between groups (*high confidence*; Section 6.3.1.5; Box 6-1). Coccolithophore blooms (*Emiliania huxleyi*) in the Bering Sea were reported for the first time during the period 1997–2000, probably in response to a 4°C warming, combined with a shallower mixed layer depth, higher light levels and low zooplankton grazing (Merico et al., 2004). Loss of multi-year Arctic sea ice has had a profound effect on the diversity, structure, and function of the epipelagic microbial assemblage (i.e., found in the layer into which enough light penetrates for photosynthesis) (Comeau et al., 2011), and further warming is likely to have even greater impacts on the food web and on ecosystem services (*medium confidence*). Warming may also have caused the southward range extension of coccolithophores in the Southern Ocean in the 2000s (Cubillos et al., 2007). However, further experimental and field observations (Giovannoni and Vergin, 2012) are required to validate model projections (Taucher

and Oschlies, 2011) of differential responses to warming by different microorganisms.

6.3.1.3. Macroalgae and Seagrasses

Macrophytes in coastal waters (Chapter 5) cover 0.6% of the world's marine areas and supply about 2 to 5% of total oceanic production (Smith, 1981; Charpy-Roubaud and Sournia, 1990; Field et al., 1998). They have limited temperature ranges and are sensitive to temperature extremes (*high confidence*), resulting in changes of photosynthesis, growth, reproduction, and survival (following the principles of Figures 6-5, 6-6; and Harley et al., 2012), with consequences for their abundance, distribution, and productivity. Ice retreat in polar areas leads to an expansion of macroalgal distribution, for example, in the Antarctic (Quartino et al., 2013).

Warm- versus cold-water-adapted species may have different sensitivities to warming and show a range of responses in distribution shifts (Lima et al., 2007). Temperate macroalgae with wide windows of thermal tolerance acclimatize by shifting these windows following seasonal temperature changes (Kübler and Davison, 1995). Antarctic and tropical macroalgae are exposed to permanently low or high temperatures, respectively, and have consequently specialized in a limited temperature range, paralleled by a low acclimatization potential (Pakker et al., 1995; Eggert et al., 2006; Gómez et al., 2011). Thus, Antarctic and tropical macroalgae appear to be most vulnerable to warming (*high confidence*; Short and Neckles, 1999). While observations in the tropics indicate that seagrasses tolerate higher temperatures than seaweeds (Campbell et al., 2006), an increase in maximum temperature by >1°C from 1988–1999 to 2002–2006 (Section 30.5.3.1.5) led to increased seagrass shoot mortality in the Mediterranean Sea (Marbà and Duarte, 2010). The molecular basis of acclimatization and evolutionary adaptation, as well as their limitation in relation to the climate regime, require further study in the macrophytes.

6.3.1.4. Animals

The mechanisms shaping the thermal performance curve and, thereby, an animal's thermal niche have been explained by the concept of "oxygen and capacity limited thermal tolerance" (OCLTT), applicable to marine invertebrates and fishes (Pörtner et al., 2010; see also Figure 6-5a, FAQ 6.2). The temperature range at which animals can function best results from optimal oxygen supply at minimal oxygen usage. At temperature extremes, oxygen supply capacity becomes constrained in relation to demand, and metabolism becomes thermally limited. Beyond upper and lower temperature thresholds (T_p, Figure 6-5a), growth, reproduction, and other key functions decrease. These thresholds change during the individual life cycle, and with body size. At large body size, limitations in oxygen supply are exacerbated and heat tolerance limits shift to lower temperatures.

Surpassing species-specific heat tolerance limits (Figure 6-5, T_p) during warming causes a reduction of abundance (Pörtner and Knust, 2007; Katsikatsou et al., 2012), coral losses (Donner et al., 2005), shifts in the seasonal timing of (zooplankton) biomass formation (Mackas et al., 1998; Schlüter et al., 2010), and changes in growth (Lloret and Rätz, 2000; Brunel and Dickey-Collas, 2010). During early life, owing to incomplete development, or as adult spawners, owing to large body size, animals may become more sensitive to warming because of narrower thermal windows (Pörtner et al., 2008). This may cause high vulnerability of winter-spawning Atlantic cod to warming winter to spring temperatures (Table 6-2). In contrast, adult bigeye, bluefin, and skipjack tuna spawn at high temperatures. They need to prevent overheating by moving to cooler (deeper) waters (Lehodey et al., 2011).

Although temperature means are still most commonly used when attributing responses of marine organisms to climate effects, temperature extremes rather than means are most often mediators of effects (e.g., Easterling et al., 2000; Wethey et al., 2011; Wernberg et al., 2013; Figure 6-5). During heat exposure near the borders of the distribution range (including the high intertidal or warming surface waters), reductions in growth, activity, and abundance accompany even small (<0.5°C) shifts in ambient temperature extremes (e.g., Takasuka and Aoki, 2006; Pörtner and Knust, 2007; Nilsson et al., 2009; Neuheimer et al., 2011). Local extinction events follow as a result of mortality or behavioral avoidance of unfavorable thermal environments (Breau et al., 2011). Shifted species distribution ranges follow temperature clines from high to low, usually along latitudes, a lateral gradient at basin scale (Perry et al., 2005; Poloczanska et al., 2013), or a vertical temperature gradient to deeper waters (*high confidence*; Dulvy et al., 2008; Section 6.5.3; see also Figure 6-5b, Box CC-MB).

Adopting OCLTT principles has enabled modeling studies to project climate effects (Section 6.5), and paleo-studies to explain climate-induced mass extinction events and evolutionary patterns in Earth history (Pörtner et al., 2005; Knoll et al., 2007). For example, long-term observations show that warming affects the body size of marine fishes (*medium confidence*). Assessing effects of warming on body size may be complicated by effects on the animal's energy budget, the changing availability and body size of prey species, community structure, species interactions, or effects of fishing (Genner et al., 2010; Cheung et al., 2013a). Below the thermal optimum, warming causes growth and weight-at-age of some juvenile or younger fish populations to increase (e.g., Brunel and Dickey-Collas, 2010; Neuheimer and Grønkjær, 2012). However, OCLTT predicts that small individuals are more heat tolerant than large ones, in line with observations of falling animal body sizes in warming oceans (Box 6-1; e.g., Daufresne et al., 2009). This trend is projected to continue into the 21st century (*medium* to *high confidence*; Cheung et al., 2013a).

Thermal windows of fishes and invertebrates roughly match ambient temperature variability (Figure 6-1) according to climate regime and seasonality (Pörtner and Peck, 2010; Sunday et al., 2012). Sub-Arctic, small, or highly mobile species are eurytherms. They function across a wide temperature range, that is, they have wide thermal windows and distribution ranges, at the expense of higher energetic costs and associated lifestyles (Pörtner, 2002a, 2006). Conversely, high polar species are stenotherms, that is, they have narrow thermal windows and low energy demand lifestyles, making them sensitive to temperature change. In a warming world, polar stenotherms will be marginalized, with no possibility to escape to colder regions (*high confidence*). However, extinction of polar species has not yet been reported. As marine fishes and invertebrates in the Southern Hemisphere are

Table 6-2 | Selected examples of species responses and underlying mechanisms to changing temperature, oxygen level and ocean acidification (OA). References are indicated by superscript numbers and in the footnote.

	Phenomenon	Key drivers	Mechanism/Sensitivity
Biogeography	Northward shift in the distribution of North Sea cod (*Gadus morhua*) stocks between 1977 and 2001. [1,2]	Temperature	Bottlenecks of high sensitivity during early life stages as well as adult spawning stage in winter/early spring.
	Shift from sardines (*Sardinops melanostictus*) to anchovies (*Engraulis japonicus*) in the western North Pacific observed between 1993 and 2003. [3,4]	Temperature	Thermal windows of growth and reproductive output are found at higher temperatures for anchovies than sardines, food preferences of the competing species being similar.
	Variable sensitivity of Pacific tuna species to the availability of dissolved O_2. Bigeye tuna routinely reach depths where ambient O_2 content is below 1.5 ml L^{-1} (≈ 60 µmoles kg^{-1}). [5, 6]	Oxygen	Oxygen transport via hemoglobin is adapted to be highly efficient supporting high metabolic rates as needed during feeding in the OMZ.
	Northward movement of species and the conversion of polar into more temperate and temperate into more subtropical system characteristics in the European Large Marine Ecosystems between 1958–2005. [7, 8]	Warming and current advection	Effects are attributed to climate change but may be influenced by nutrient enrichment and overfishing.
Abundance	Increase in abundance of arctic boreal plankton species, notably the copepods *Calanus hyperboreus*, *Calanus glacialis* and the dinoflagellate *Ceratium arcticum* between 1960 and 2000 in the Newfoundland Shelf, Northwest Atlantic. [9,10]	Temperature	Temperature sensitivity of phyto- and zooplankter resulting from cooling due to increased influx of Arctic water.
	A benthic fish species, the eelpout (*Zoarces viviparus*) at its southern distribution limit, the German Wadden Sea, displayed abundance losses during warming periods and rising summer extreme temperatures between 1993 and 2005, with early disappearance of the largest individuals. [11]	Temperature	Temperature extremes exceed organism's thermal windows, with largest individuals being relatively less tolerant to high temperature than smaller individuals.
	Variable sensitivities to OA within and across animal phyla (Figure 6-10b). [12–21]	Anthropogenic OA, sea water acidification by elevated pCO_2 in OMZs, upwelling areas, involving anthropogenic ocean acidification.	Lowered extracellular (blood plasma) pH causing a lowering of the rates of ion exchange and metabolism in muscle or liver (hepatocytes) of vertebrates and invertebrates. High sensitivity at reduced energy turnover in tissues and/or whole organism by reduced ion exchange, use of more energy efficient transport mechanisms, reduced protein synthesis, enhanced nitrogen release from amino acid catabolism and protein degradation, slower growth.
Phenology	Migration time of pink salmon (*Oncorhynchus gorbuscha*) in Alaska is almost two weeks earlier in 2010s relative to 40 years ago. [22]	Warming	Rapid microevolution for earlier migration timing.
	In the waters around the UK, during a period of warming between 1976 and 2005, the seasonal timing of biological events of all major marine taxonomic groups (plant/phytoplankton, invertebrate and vertebrates) advanced, on average, by 0.31 to 0.43 days $year^{-1}$. [23]	Warming	Sensitivity to seasonal temperature changes as a result of specific thermal windows of different organisms.
Body size and growth	Asymptotic body sizes of different populations of Atlantic cod (*Gadus morhua*) and Atlantic Herring (*Clupea harengus*) are negatively related to temperature. [24, 25]	Warming	At large body size, oxygen supply limitations are exacerbated and the organism reaches its long-term heat tolerance limits at lower temperatures, thus limiting the maximum body size that can be reached.

1. Perry et al. (2005); 2. Pörtner et al. (2008); 3. Takasuka et al. (2007); 4. Takasuka et al. (2008); 5. Lehodey et al. (2011); 6. Seibel (2011); 7. Beaugrand et al. (2009); 8. Philippart et al. (2011); 9. Johns et al. (2001);10. Greene and Pershing (2003); 11. Pörtner and Knust (2007); 12. Reipschläger and Pörtner (1996); 13. Pörtner et al. (2000); 14. Vezzoli et al. (2004); 15. Langenbuch and Pörtner (2003); 16. Fernández-Reiriz et al. (2011); 17. Langenbuch and Pörtner (2002);18. Langenbuch et al. (2006); 19. Michaelidis et al. (2005); 20. Pörtner et al. (1998); 21. Stumpp et al. (2012); 22. Kovach et al. (2012); 23. Thackeray et al. (2010); 24. Taylor (1958); 25. Brunel and Dickey-Collas (2010).

adapted to less variable ocean temperatures than those in the Northern Hemisphere (Jones et al., 1999; Figure 6-1), they may generally be more vulnerable to warming extremes than Northern ones. Tropical species (with thermal windows of intermediate width) live close to the highest temperatures tolerated by marine animals (Figure 6-6). Vulnerability is, therefore, highest for polar stenotherms, similar or lower for tropical, and lowest for temperate species (*high confidence*).

Short-term shifts in thermal thresholds of an individual organism may happen over days and weeks, such as during seasonal acclimatization. Long-term shifts occur over many generations during evolutionary adaptation of a population to cooler or warmer climates (Figure 6-5a; Pörtner, 2006; Pörtner et al., 2008; Eliason et al., 2011). Both acclimatization and adaptation involve adjustments in biochemical characters (membranes, enzymes); however, the capacity to shift those boundaries is limited and depends on the species and the prevailing climate regime (Pörtner et al., 2008, 2012). Ocean acidification, hypoxia, food availability, and stress affect those limits (Section 6.3.5; Figure 6-5a).

Local adaptation may reduce climate vulnerability at the species level, by causing functional and genetic differentiation between populations, thereby enabling the species to cover wider temperature ranges and live in heterogeneous environments. Local adaptation on small spatial scales is particularly strong in intertidal organisms (Kelly et al., 2012). On larger scales, the widening biogeographic and roaming ranges of

Northern Hemisphere eurytherms into Arctic waters (Pörtner et al., 2008) are supported by the differentiation into populations with diverse thermal ranges, combined with high acclimatization capacity. By contrast, such capacity is small in high polar, for example, Antarctic species (Peck et al., 2010). Tropical reef fishes undergo rapid warm acclimation across generations (Donelson et al., 2012) but some may approach animal heat limits. The rates, mechanisms, and limits of thermal acclimatization and evolutionary adaptation are poorly understood (*low confidence*).

6.3.1.4.1. Warm- and cold-water coral communities

Tropical corals live in shallow water and differ from most other animals by hosting dinoflagellates (*Symbiodinium* sp.) in their tissues, which provide the host with organic carbon from photosynthesis and with nitrogen and enable the corals to build and sustain carbonate reefs (Box CC-CR). High light, rapid salinity changes, and small increases in temperature can trigger "coral bleaching", the loss of symbionts and tissue color. In case of warming, early steps involve shifts in the photosynthetic processing of light, generating Reactive O_2 Species (ROS) that may in turn damage the symbionts (Hoegh-Guldberg and Smith, 1989; Glynn and D'Croz, 1990; Jones et al., 1998; Hoegh-Guldberg, 1999). Mass bleaching correlates with small temperature anomalies (+1°C to 2°C of the long-term summer maximum, satellite observations), causing mortalities (Goreau and Hayes, 1994; Strong et al., 2011) and decreasing coral abundance, on average by 1 to 2% per year (*high confidence*; Bruno and Selig, 2007; see also Box CC-CR; Section 30.5.6).

The degree of impact will depend on the coral reefs' adaptability to thermal stress and the interaction of multiple drivers (Meissner et al., 2012; Teneva et al., 2012; see also Box CC-CR). Such capacity is suggested by different heat tolerances among coral genera (Hoegh-Guldberg and Salvat, 1995; Loya et al., 2001), the exchange of genetic clades of *Symbiodinium* with more tolerant varieties (Baker, 2001; Jones et al., 2008), as well as acclimatization phenomena (Howells et al., 2012).

Studies of the thermal sensitivity of deeper-living cold-water corals (without endosymbionts) are scarce. One species, *Lophelia pertusa*, responds to about 3°C warming with a threefold increase in metabolic rate (Dodds et al., 2007), indicating a narrow thermal window in the cold (cf. Pörtner, 2006).

6.3.1.5. Ecosystems

Heat exposure of ecosystem engineers may threaten the existence of a whole ecosystem. During the last warm interglacial period equatorial coral reefs deteriorated and retreated (Kiessling et al., 2012), a finding emphasizing their thermal sensitivity (Veron et al., 2009) and showing that warming oceans can reach temperatures well beyond the upper heat limits of distinct animal groups and marine animals overall (Figure 6-6). In the present-day Great Barrier Reef, a large-scale survey found diverse coral types along a climatic gradient, with no consistent response to climatic drivers (Hughes et al., 2012). However, warm-induced bleaching has contributed to the progressive decrease in live coral cover observed over the last decades (De'ath et al., 2012; see also Box CC-CR; Section 30.5.6).

Within ecosystems, shifting competitive or trophic interactions, differential risks for species extinctions and, thereby, scenarios of community-level responses to temperature change (Urban et al., 2012; Milazzo et al., 2013) can be traced back to changing differences in the performance of participating animal species (Figure 6-7; e.g., Cairns et al., 2008; Harley, 2011; Pörtner, 2012). Knowledge is insufficient to assess interactions of species from different domains, impeding a deeper understanding of shifting distributions, abundances, community assemblages, and food webs in space and time (*low confidence* in current understanding; Parmesan and Matthews, 2005).

For example, in a coastal microcosm (small-scale, simplified experimental ecosystem) resident heterotrophic bacteria were stimulated by warming more than a laboratory-reared phytoplankter (Wohlers-Zöllner et al., 2011). Also, high- to low-latitude transects in both the North and South Atlantic revealed a shift between cold and warm waters, from photo-autotrophs (gaining energy from photosynthesis) to chemo-heterotrophs (Hoppe et al., 2002). Thermal stimulation of bacteria over phytoplankton has biogeochemical implications, for example, microbially mediated CO_2 flow to the atmosphere might increase (Sarmento et al., 2010). The principles and wider applicability of these findings require further investigation (*limited evidence*, *low agreement*; Kirchman et al., 2009).

Observations of shifting distributions and phenologies, reproduction, and range shifts of phytoplankton, zooplankton, other invertebrates, fishes, and seabirds in pelagic and coastal marine ecosystems have at least partly been attributed to temperature-mediated biological responses (*high confidence*; see also Figure 6-8; Box 6-1; Box CC-MB). In the North Atlantic as a key example, many biological events have been occurring earlier in the year (*robust evidence*, *high agreement*; Box 6-1; Section 30.5.1.1.1). Species richness has increased as a result of shifts in ranges and abundances. In the Norwegian and Barents Seas, a time series (1959–2006) of four commercial fish species and their zooplankton prey showed that climate shapes population growth rates through complex influences early in life, including direct temperature effects on growth, indirect effects via the biomass of zooplankton prey, and delayed feedback effects through predators (Stige et al., 2010). Differential species responses to temperature and trophic amplification were demonstrated to modify species interactions at five trophic levels: primary producers (phytoplankton); primary, secondary, and tertiary consumers (zooplankton, fishes, and jellyfishes); and benthic detritivores (echinoderms and bivalves) (Kirby and Beaugrand, 2009). Also, the responses of various plankton functional groups, such as diatoms, dinoflagellates, and copepods, to warming are not synchronous, resulting in predator-prey mismatches that carry over to higher trophic levels (*high confidence*; Edwards and Richardson, 2004; Costello et al., 2006; see also Figure 6-7a; Section 6.3.6). In the intertidal, warming-induced changes in relative species ranges lead to shifts in dominance through competitive interactions and to modifications in predator pressure (Poloczanska et al., 2008; Harley, 2011). Trans-Arctic interchange of species between Atlantic and Pacific has happened repeatedly in warm periods of the Pleistocene (Dodson et al., 2007) and may occur again, now facilitated by ballast transport by enhanced trans-Arctic shipping (*low* to *medium confidence*).

Warming may increase the risk of disease outbreaks or parasite infections, in marine organisms and ecosystems, and ultimately, humans (*medium*

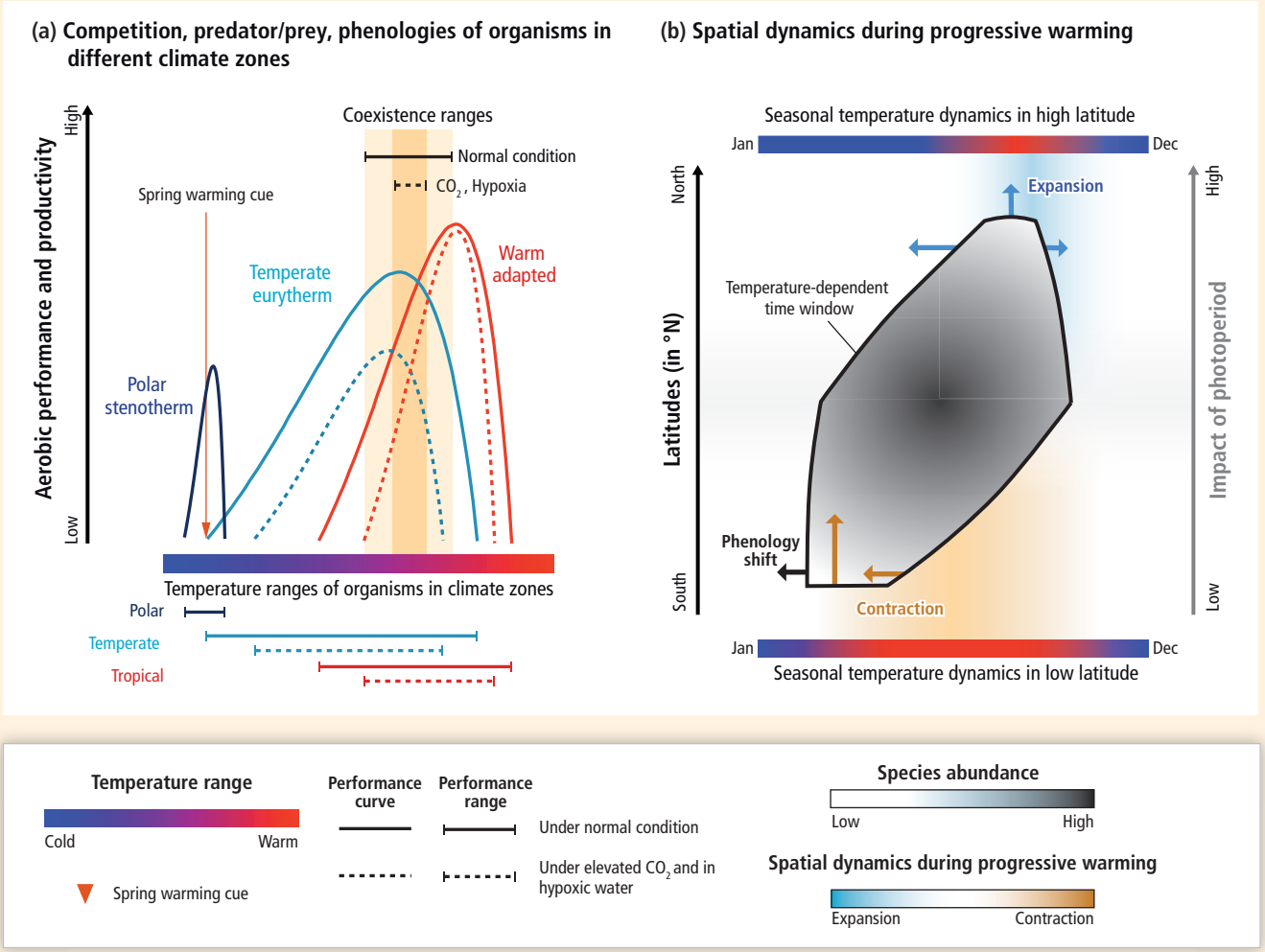


Figure 6-7 | Role of thermal tolerance and performance of organisms at ecosystem level. (a) Thermal tolerance ranges (Figure 6-5) differ between species across polar, temperate, and tropical climate zones, then overlap between coexisting species. Shifting temperatures and specific effects of additional drivers on the respective performance curves (dashed lines) change the fitness of coexisting species relative to each other as well as their temperature range of coexistence (after Pörtner and Farrell, 2008). Warming alters the timing of seasonal activities (e.g., elicited by spring warming cues) to earlier, or can benefit only one of two interacting species (e.g., in predator–prey dynamics or competition), causing shifts in predominance. (b) During climate warming a largely unchanged thermal range of a species causes it to follow its normal temperatures as it moves or is displaced, typically resulting in a poleward shift of the biogeographic range (exemplified for the Northern Hemisphere; modified after Beaugrand, 2009). The polygon delineates the distribution range in space and seasonal time; the level of gray denotes abundance. The Southern time window of tolerated temperatures shifts to earlier and contracts, while the Northern one dilates (indicated by arrows). Species display maximum productivity in low latitude spring, wide seasonal coverage in the center, and a later productivity maximum in the North. The impact of photoperiod (length of daily exposure to light) increases with latitude (gray arrow). Water column characteristics or photoperiod may overrule temperature control in some organisms (e.g., diatoms), limiting northward displacement.

confidence; Altizer et al., 2013; Burge et al., 2014). Some marine pathogens and protist diseases are shifting their distribution poleward as oceans warm (e.g., Baker-Austin et al., 2013; Burge et al., 2014). Climate change may weaken the immune response of hosts, particularly fishes and invertebrates, and increase their susceptibility to disease, as observed during warming in coral reefs of the Pacific and Caribbean (Harvell et al., 2009). Global outbreak frequencies of jellyfish aggregations may follow rising sea surface temperatures (SSTs) (*low confidence*; Mills, 2001; Purcell and Decker, 2005), but evidence is inconclusive. Some studies report an increasing trend (Brotz et al., 2012) and others do not support this view (Condon et al., 2013).

In conclusion, organisms live in limited temperature ranges and are sensitive to temperature extremes (*very high confidence*). Temperature governs the biogeography, diversity, development, reproduction, behavior, and phenology of marine species as well as the composition of communities in both pelagic and benthic systems and the seasonal timing of relevant processes (phenology) (*very high confidence*). Ecosystems functioning at the coldest temperatures and warm adapted ones existing at their upper thermal limits are more sensitive (*medium confidence*).

6.3.2. Carbon Dioxide Effects

Evidence for biological effects of ocean acidification stems from paleo-observations (Section 6.1.2), few observations in the field (Section 6.3.2.5), studies at volcanic CO_2 seeps as natural analogs, and mostly from short- to medium-term (hours to months) experiments in the

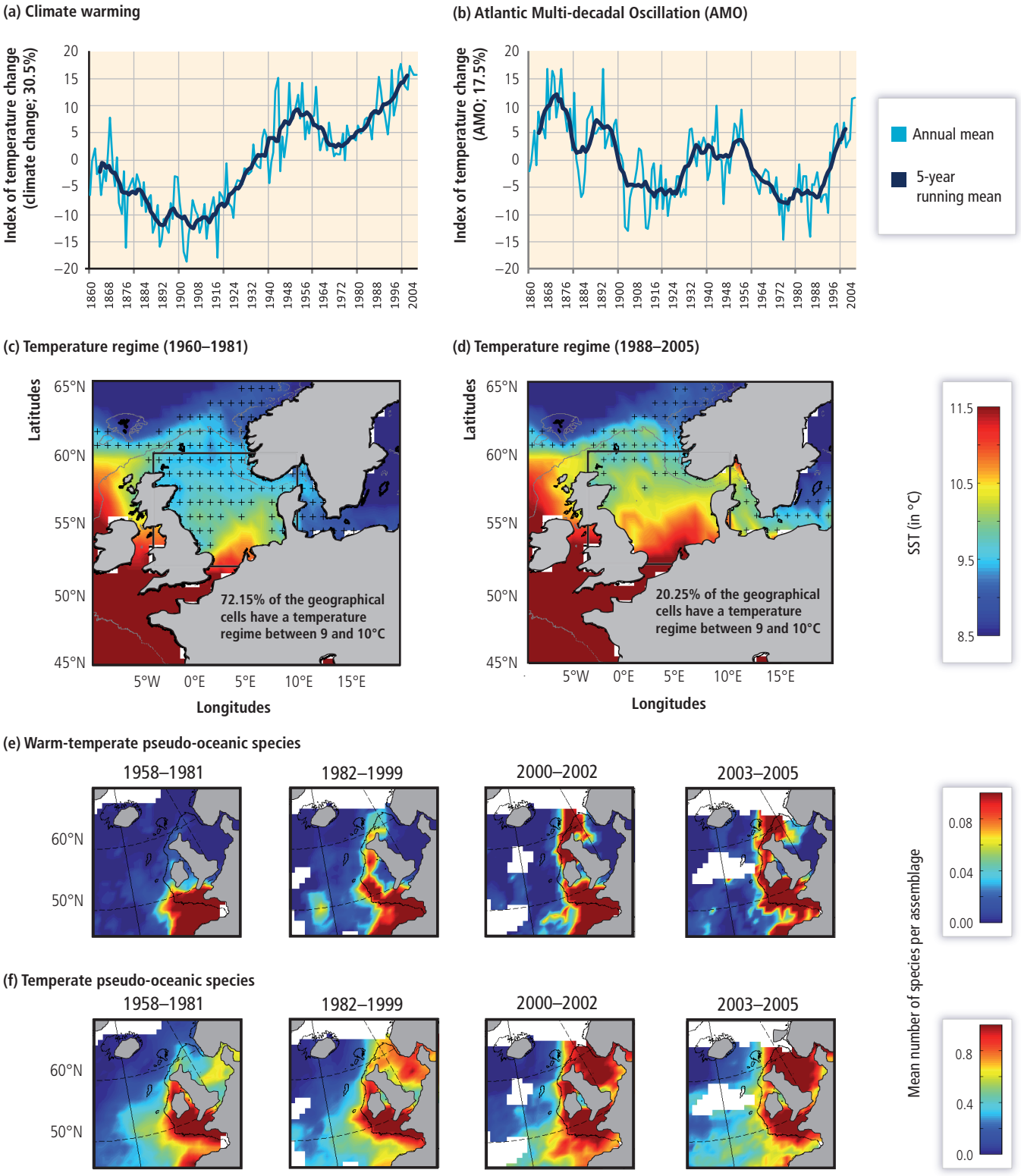
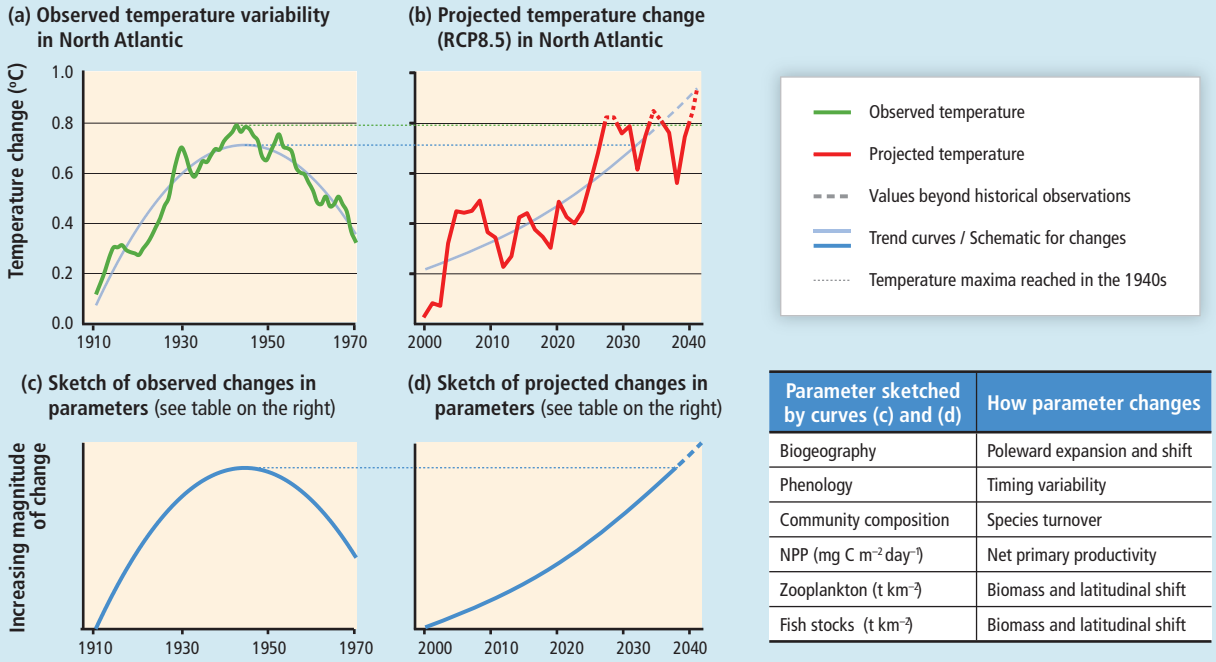


Figure 6-8 | Multi-decadal changes in ecosystem structure in the Northeast Atlantic driven by warming from both anthropogenic climate change and natural climate variability. (a) Index of temperature change over the North Atlantic (31°N to 65°N and 99°W to 11°E) reflecting climate change. This index is the first principal component (i.e., explaining 30.5% of observed variability) based on a principal component analysis (PCA) performed on sea surface temperature. (b) Index of temperature change (17.5% of observed variability) reflecting the Atlantic Multi-decadal Oscillation (AMO). The index is the second principal component. (c, d) Observed mean annual sea surface temperature in the North Sea during 1960–1981 (c) and 1988–2005 (d). The location of the critical thermal boundary (9°C to 10°C) is indicated by "+." (e) Long-term changes in the mean number of warm-temperate pseudo-oceanic species from 1958 to 2005. (f) Long-term changes in the mean number of temperate pseudo-oceanic species from 1958 to 2005. The period 1958–1981 was a period of relative stability and the period 1982–1999 was a period of rapid northward shifts, indicating that the abrupt ecosystem shift observed in the North Sea was part of a large-scale response of the zooplankton biodiversity to warming temperatures (see a–d). Average values are below 1 because they are annual averages. Note that the color bar is 10-fold smaller for warm-temperate pseudo-oceanic species because these species are less frequently observed than their temperate counterparts. Panels (a) and (b) from Edwards et al. (2013), and (c)–(f) from Beaugrand et al. (2008, 2009).

Box 6-1 | An Atlantic Ocean Example: Long-Term Responses of Pelagic Organisms and Communities to Temperature

Long-term observations (Sections 6.1.2, 30.5.1.1.1) encompassing the pelagic Northeast Atlantic over a 50-year period and longer (Figures 6-8, 6-9) show changes in the seasonal abundance of phytoplankton, rapid northerly displacements of temperate and subtropical zooplankton (e.g., calanoid copepods) and phytoplankton (e.g., dinoflagellates and diatoms), and the resulting changes in the ecosystem functioning and productivity (*high confidence*; Edwards et al., 2001; Beaugrand et al., 2002; Edwards and Richardson, 2004). The range limit of warm water copepods shifted by 10° north since 1960 (Beaugrand et al., 2009), with attendant mismatch in the seasonal timing of trophic levels (predators and prey) and functional groups (Edwards and Richardson, 2004). Modes of climate variability reflected in climate indices like the Northern Hemisphere Temperature (NHT) and the North Atlantic Oscillation (NAO) over multi-decadal periods accompanied these changes (Figure 6-1). In cooler regions, increased phytoplankton activity caused by warming favored growth, resulting in the observed increase in phytoplankton biomass, whereas a decrease in nutrient supply would have prevented growth in warmer regions and caused a decrease in biomass (Richardson and Schoeman, 2004; see also Section 6.3.4). Hinder et al. (2012) attributed a recent decline in North Sea dinoflagellates relative to diatoms to warming, increased summer windiness, and thus water column turbulence. The ecosystem response to natural climate variability in the past provides a glimpse into the climate-induced changes of the near future (Figure 6-9).



Parameter sketched by curves (c) and (d)	How parameter changes
Biogeography	Poleward expansion and shift
Phenology	Timing variability
Community composition	Species turnover
NPP (mg C m^{-2} day^{-1})	Net primary productivity
Zooplankton (t km^{-2})	Biomass and latitudinal shift
Fish stocks (t km^{-2})	Biomass and latitudinal shift

Figure 6-9 | Schematic depiction of observed effects of approximately 1°C ocean warming in the northern North Atlantic driven by climate variability (a,c) versus effects expected from anthropogenic climate change (b,d). (a) Transient warming and cooling associated with Atlantic Multi-decadal Oscillation (AMO) variability (Drinkwater, 2006), based on the Kola Section temperatures (0 to 200 m; Stations 3 to 7, 71.5° to 72.5°N, 33.5°E) in the Barents Sea obtained from http://www.pinro.ru and filtered using a 20-year running mean. Similar trends occurred across most of the northern North Atlantic although the amplitude and timing of the peaks and troughs varied spatially. (b) Warming driven by climate change for the same region (Representative Concentration Pathway 8.5 (RCP8.5) simulations averaged from Coupled Model Intercomparison Project Phase 5 (CMIP5) models, computed as the mean over the upper 200 m in the grid box (2.5° × 2.5°) centered at 71.25°N and 33.75°E). (c) Warming and subsequent cooling in the northern North Atlantic during the period shown in (a) resulted in complex multi-faceted changes (shown schematically) in net primary production (NPP), zooplankton biomass, and fish stock abundances. There was a general poleward shift and range expansion of many commercial (e.g., Atlantic herring, Atlantic cod, haddock) and non-commercial species, reversed during the subsequent cooling period. Poleward shifts in spawning areas (e.g., Atlantic cod) were also reversed as the waters cooled. Shifts in seasonal timing (phenology) and community composition were influenced by earlier arrivals and later retreat of migratory fish (not shown). For more details see Drinkwater (2006). (d) Projected effects of climate mediated warming on northern sub-polar and polar biota based on model projections of altered NPP (Bopp et al., 2013), and of the range shift of exploited fishes and invertebrates (Cheung et al., 2009, 2013a). The projected trends in (d) will differ with latitude, for example, decreased NPP at lower latitudes and no significant change to NPP in temperate waters (Bopp et al., 2013). Higher NPP supported and is projected to support higher trophic levels at high latitudes (c,d; Section 6.3.4). Note that climate variability will be superimposed on anthropogenic warming (b; see Figures 6-1, 6-8a,b). Dashed lines indicate projected changes to continue beyond the range of historical observations.

Continued next page →

Box 6-1 (continued)

In regions of high vulnerability to climate, mild warming can trigger rapid and substantial ecosystem shifts, offering a way to anticipate future changes (Figure 6-9). In line with the increased understanding of physiology (Section 6.3.1.1), warming in the temperate to polar North Atlantic was paralleled by a reduction in the average body lengths of about 100 copepod species, from 3 to 4 mm to 2 to 3 mm (Beaugrand et al., 2010). Warming also correlated with an increase in species richness among copepods and within the dinoflagellate genus *Ceratium*. In diatoms, which are major contributors to carbon export (Armbrust, 2009), warming and decreasing annual variability in SST resulted in lower diversity, smaller size, and reduced abundance (Beaugrand et al., 2010). Morán et al. (2010) found that temperature alone explained 73% of the variance in the contribution of small cells (picophytoplankton) to total phytoplankton biomass in the eastern and western temperate North Atlantic from –0.6 to 22°C. More recently, Marañón et al. (2012) analyzed data from polar, sub-polar, and tropical regions and suggested that nutrient availability may influence cell size more than temperature.

The ecosystem regime shift observed in North Sea plankton in the late 1980s involved an increase in phytoplankton stocks and changes in species composition and abundance among holozooplankton (animals that are planktonic for their entire lifecycle) (Reid et al., 2001; Kirby and Beaugrand, 2009; Kirby et al., 2009; Lindley et al., 2010). This shift was paralleled by the northward propagation of a critical thermal boundary (CTB, i.e., the boundary of the sub-polar gyre) between the temperate and the polar biomes (Beaugrand et al., 2008; see also Box CC-PP, Figure 1). Warming to above the CTB coincided with pronounced and large-scale variations in phytoplankton productivity, an increase in calanoid copepod diversity (Beaugrand et al., 2008) and herring abundance (Schlüter et al., 2008), a reduction in the mean size of calanoids, and a decrease in the abundance of southern Atlantic cod populations in the North Atlantic Ocean (e.g., the North Sea; Pörtner et al., 2008; Beaugrand et al., 2010). These patterns also extend to the southern North Sea, where elevated salinities and average warming by 1.6°C, both in summer and winter between 1962 and 2007, expanded the time window for growth of microalgae and possibly supported the invasion and increase in numbers of warm-adapted silicified diatoms (Wiltshire et al., 2010). Recent findings indicate a regime shift in the Bay of Biscay and the Celtic and the North Seas in the mid to end 1990s (Luczak et al., 2011). Changing plankton composition and changing abundances of both sardine and anchovies (Raab et al., 2013) paralleled stepwise warming.

Northward range extensions or redistributions in fishes were largest along the European Continental shelf and attributed to regional warming, for example, by 1.0°C from 1977 to 2001 in the North Sea, with winter warming being closely correlated with the shift of Atlantic cod (Perry et al., 2005; see also Section 6.3.1). Similar trends were observed due to warming by 1°C to 2°C in the waters south and west of Iceland during the past 15 years (Valdimarsson et al., 2012). In the Northwest Atlantic Arctic and sub-Arctic, winter and spring warming caused expansion of the area matching the thermal optimum of Atlantic salmon at 4°C to 8°C and caused greater growth (Friedland and Todd, 2012). Pelagic sardines and anchovies entered the North Sea in the early to mid-1990s, after about 40 years of absence, in response to intensified NAO and AMO (Alheit et al., 2012). Red mullet and bass extended into western Norway; Mediterranean and northwest African species extended to the south coast of Portugal (Brander et al., 2003; Beare et al., 2004; Genner et al., 2004; see also Section 30.5.1.1.4).

In the Northwest Atlantic cooling and freshening occurred during the late 1980s to early 1990s and seemed to have the opposite effect, as capelin and their predator, Atlantic cod, shifted farther south (Rose and O'Driscoll, 2002). Between the early 1990s and mid-2000s in the Northwest Atlantic sub-polar gyre, phytoplankton biomass increased, due to warming. At the same time, Arctic copepod species became more abundant, due to increased influx of Arctic water (Head and Pepin, 2010). Although temperatures have risen on the Newfoundland Shelf (Colbourne et al., 2011), capelin and cod remain scarce for reasons probably unrelated to climate (DFO, 2011a,b). Farther south, Arctic freshwater inflows caused freshening and increased stratification of the area around the Gulf of Maine throughout the 1990s, resulting in enhanced phytoplankton abundance, a larger and later fall bloom, increased abundance of small copepods, and a decrease in the large copepod *Calanus finmarchicus* (deYoung et al., 2004; Pershing et al., 2005, 2010). Various fish species showed poleward shifts in distribution (Table 6-2) that were associated with reduced survival of larval cod (Mountain and Kane, 2010) and fewer right whale calves (Greene et al., 2003), but increased herring abundance (Greene and Pershing, 2007).

Frequently Asked Questions

FAQ 6.3 | Why are some marine organisms affected by ocean acidification?

Many marine species, from microscopic plankton to shellfish and coral reef builders, are referred to as calcifiers, species that use solid calcium carbonate ($CaCO_3$) to construct their skeletons or shells. Seawater contains ample calcium but, to use it and turn it into $CaCO_3$, species have to bring it to specific sites in their bodies and raise the alkalinity (lower the acidity) at these sites to values higher than in other parts of the body or in ambient seawater. That takes energy. If high CO_2 levels from outside penetrate the organism and alter internal acidity levels, keeping the alkalinity high takes even more energy. The more energy is needed for calcification, the less is available for other biological processes such as growth or reproduction, reducing the organisms' weight and overall competitiveness and viability.

Exposure of external shells to more acidic water can affect their stability by weakening or actually dissolving carbonate structures. Some of these shells are shielded from direct contact with seawater by a special coating that the animal makes (as is the case in mussels). The increased energy needed for making the shells to begin with impairs the ability of organisms to protect and repair their dissolving shells. Presently, more acidic waters brought up from the deeper ocean to the surface by wind and currents off the Northwest coast of the USA are having this effect on oysters grown in aquaculture.

Ocean acidification affects not only species producing calcified exoskeletons. It affects many more organisms either directly or indirectly and has the potential to disturb food webs and fisheries. Most organisms that have been investigated display greater sensitivity at extreme temperatures so, as ocean temperatures change, those species that are forced to exist at the edges of their thermal ranges will experience stronger effects of acidification.

laboratory or field, exposing organisms to projected future CO_2 levels (Sections 6.3.2.1-4). A surging number of studies is providing evidence that rising CO_2 levels will increasingly affect marine biota and interfere with ecological and biogeochemical processes in the oceans (*high confidence*; FAQs 6.2, 6.3).

6.3.2.1. Principles

The absorption of rising atmospheric CO_2 by oceans and organisms changes carbonate system variables in the water and in organism internal fluids, that is, the relative proportions of CO_2, carbonate, bicarbonate, and hydrogen ions (pH). Internal pH must be tightly controlled, as some processes, such as calcification, release protons thereby affecting pH and as other biochemical processes are pH sensitive. Accumulation of CO_2 and the resulting acidification can also affect a wide range of organismal functions, such as membrane transport, calcification, photosynthesis in plants, neuronal processes in animals, growth, reproductive success, and survival. Effects translate from organism to ecosystem.

The capacity of organisms to resist and compensate for the CO_2-induced acidification of internal fluids depends on acid-base regulation, that is, the capacity of ion exchange to accumulate bicarbonate internally, an aspect unexplored in many phyla (*low* to *medium confidence*; Figure 6-10a; e.g., animals: Heisler, 1986; Claiborne et al., 2002; Pörtner, 2008; phytoplankton: Taylor et al., 2011; see also FAQ 6.3).

In unicellular microbes the regulation of intracellular pH may play a key role in modulating CO_2 responses (Taylor et al., 2011). Findings in invertebrates and fish indicate an additional role for extracellular pH (Figure 6-10a); effective pH values may vary between species. Organisms pre-adapted to elevated CO_2 may minimize the decrease in pH (acidosis). They may also modify their sensitivity such that they respond less or not at all to the acidosis. Recent evidence, however, emphasizes a role for acid-base regulation in a natural low-pH setting. Between two urchin species, only the one successful in maintaining its setpoints of extracellular pH is able to settle close to volcanic CO_2 seeps (Calosi et al., 2013). Compensating for the acidosis may cause increased energy demand and respiration rates. In general, such capacity rises with metabolic energy turnover, for example, it is higher in more active marine animals, such as fishes, cephalopods, and pelagic copepods, and in mobile coastal crabs compared to sessile species (Pörtner et al., 2005, 2011; Ishimatsu et al., 2008; Melzner et al., 2009; Ishimatsu and Dissanayake, 2010; see also Table 6-3). This matches the sensitivity distribution seen among animals at the phylum level (*medium confidence*; Figure 6-9b).

Some species have lower metabolic rates in response to acidosis (Pörtner et al., 1998; Michaelidis et al., 2005; Pörtner, 2008; Liu and He, 2012; Navarro et al., 2013); others display increased energy turnover and food ingestion rates, possibly indicating a capacity to resist acidification effects (Parker et al., 2011; Saba et al., 2012). The effects of the acidosis on various processes relevant to fitness may explain changes in whole-organism energy demand, probably paralleled by modified ion exchange, protein synthesis, and growth and feeding rates. The magnitude of effect depends on the CO_2 concentrations reached (Figure 6-10b).

The internal formation of carbonate from bicarbonate is essential to calcification, which is the formation of solid $CaCO_3$ in internal or external

calcified structures, used for defense and structural support. Calcification usually occurs in separate body or cell compartments, where pH and thus CO_3^{2-} concentration and saturation Ω (Section 6.1.1) are maintained at values higher than in other body fluids or ambient water (Taylor et al., 2011; Trotter et al., 2011; McCullough et al., 2012; Venn et al., 2013). CO_2 impedes the formation of carbonate such that calcification rate decreases. It may be maintained by enhanced transport of ions, incurring elevated energetic costs (Figure 6-10).

External carbonate structures like shells rely on ambient seawater being supersaturated with carbonates. Decreasing oceanic carbonate levels reduce the saturation levels (Ω) of calcite or aragonite in the water. Reduction to below unity may lead to the corrosion of carbonate shells (FAQ 6.3). However, many species protect their shells from direct contact with seawater by various types of organic coating (e.g., a periostracum in mollusks and brachiopods, an epicuticle covering the carapace of crustaceans, an epidermis covering the tests of urchins, epithelial tissue covering aragonite in corals, and coralline algae precipitating $CaCO_3$ (mostly Mg-calcite) within their cell wall). A meta-analysis of the effects of ocean acidification on biological processes indicates that reductions in the rate of net calcification (calcification minus dissolution) and survival are the most uniform responses across organisms studied, relative to other, more variable impacts such as reduced growth, development, and abundance (Kroeker et al., 2013; see also Box CC-OA).

Some organisms benefit from elevated CO_2 partial pressures (pCO_2). Photosynthesis and/or nitrogen fixation in selected microorganisms are impacted by OA, but effects are species or taxon specific, possibly depending on how they acquire carbon, that is, the presence and in particular the type, capacity, and energetic costs of carbon-concentrating mechanisms (CCMs; Giordano et al., 2005; Kranz et al., 2011).

A comprehensive picture of responses to CO_2 requires consideration of variable sensitivities between species and life stages and taxon-specific sensitivity distributions, as shown by a meta-analysis of animal data (Wittmann and Pörtner, 2013; see also Figure 6-10b). Echinoderms, bivalves, gastropods, and corals begin to respond negatively at lower CO_2 levels than crustaceans or cephalopods (Figure 6-10b). This sensitivity

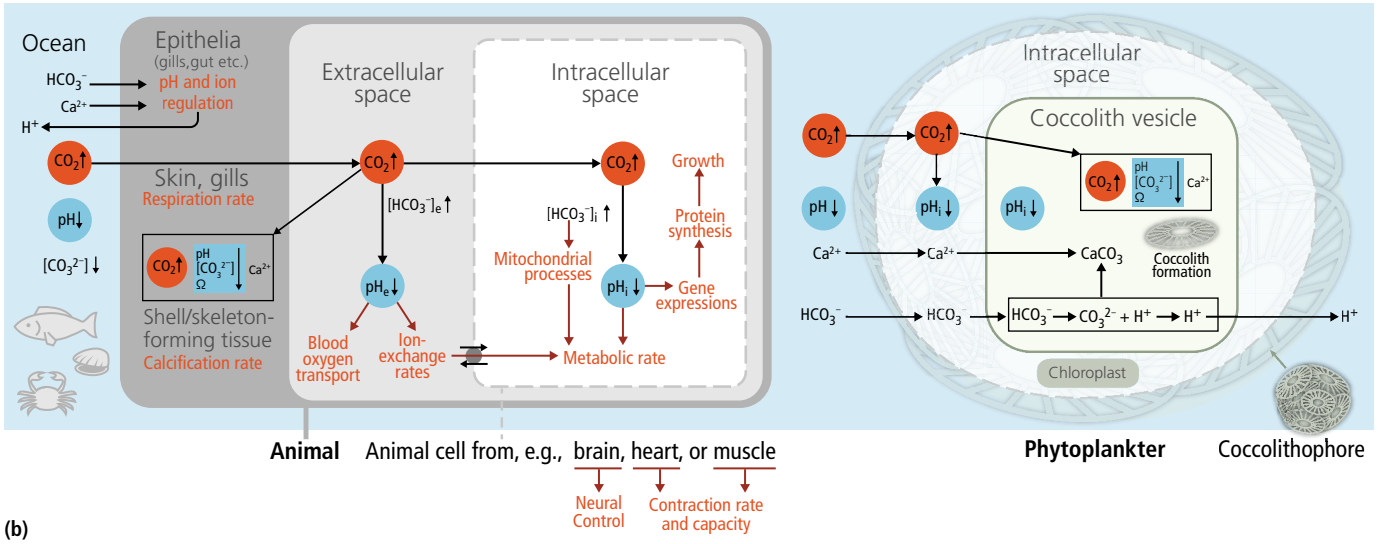
Table 6-3 | Tolerances to ocean acidification in marine taxa, assessed from laboratory and field studies of species in the CO_2 partial pressure (pCO_2) range from <650 to >10000 µatm, compared to present day atmospheric levels of 400 µatm. (It should be noted that anthropogenic CO_2 emissions add to the natural variability of CO_2 concentrations in marine environments, which can reach much higher than atmospheric levels.) Variables studied include growth, survival, calcification, metabolic rate, immune response, development, abundance, behavior, and others. Neither all life stages, nor all variables, including the entire range of CO_2 concentrations, were studied in all species. *Confidence* is based on the number of studies, the number of species studied, and the agreement of results within one group. + denotes that possibly more species or strains (genetically distinct populations of the same species) were studied, as only genus or family were specified; beneficial: most species were positively affected; vulnerable: more than 5% of species in a group will be negatively affected by 2100; tolerant: more than 95% of species will not be affected by 2100. RCP 6.0: Representative Concentration Pathway (RCP) with projected atmospheric pCO_2 = 670 µatm; RCP 8.5: pCO_2 = 936 µatm in 2100 (Meinshausen et al., 2011). *Confidence* is limited by the short- to medium-term nature of various studies and the lack of sensitivity estimates on evolutionary time scales, that is, across generations (see separate reference list, Online Supplementary Material). Note that the assessment of variability between species from the same animal phylum has revealed an increase in the fraction of sensitive species with rising CO_2 levels; see Figure 6-10.

Taxon	No. of studies	No. of parameters studied	Total no. of species studied	pCO_2 where the most vulnerable species is negatively affected or investigated pCO_2 range[a] (µatm)	Assessment of tolerance to RCP 6.0 (*confidence*)	Assessment of tolerance to RCP 8.5 (*confidence*)
Cyanobacteria	17	5	9+	180–1250[a]	Beneficial (*low*)	Beneficial (*low*)
Coccolithophores	35	6	7+	740	Tolerant (*low*)	Vulnerable (*medium*)
Diatoms	22	5	28+	150–1500[a]	Tolerant (*low*)	Tolerant (*low*)
Dinoflagellates	12	4	11+	150–1500[a]	Beneficial (*low*)	Tolerant (*low*)
Foraminifers	11	4	22	588	Vulnerable (*low*)	Vulnerable (*medium*)
Seagrasses	6	6	5	300–21000[a]	Beneficial (*medium*)	Beneficial (*low*)
Macroalgae (non-calcifying)	21	5	21+	280–20812[a]	Beneficial (*medium*)	Beneficial (*low*)
Macroalgae (calcifying)	38	10	36+	365	Vulnerable (*medium*)	Vulnerable (*high*)
Warm-water corals	45	13	31	467	Vulnerable (*medium*)	Vulnerable (*high*)
Cold-water corals	10	13	6	445	Vulnerable (*low*)	Vulnerable (*medium*)
Annelids	10	6	17+	1200	Tolerant (*medium*)	Tolerant (*medium*)
Echinoderms	54	14	35	510	Vulnerable (*medium*)	Vulnerable (*high*)
Mollusks (benthic)	72	20	38+	508	Vulnerable (*medium*)	Vulnerable (*high*)
Mollusks (pelagic)	7	8	8	550	Vulnerable (*low*)	Vulnerable (*medium*)
Mollusks (cephalopods)	10	8	5	2200 (850 for trace elements)	Tolerant (*medium*)	Tolerant (*medium*)
Bryozoans	7	3	8+	549	Tolerant (*low*)	Vulnerable (*low*)
Crustaceans	47	27	44+	700	Tolerant (*medium*)	Tolerant (*low*)
Fish[b]	51	16	40	700	Vulnerable (*low*)	Vulnerable (*low*)

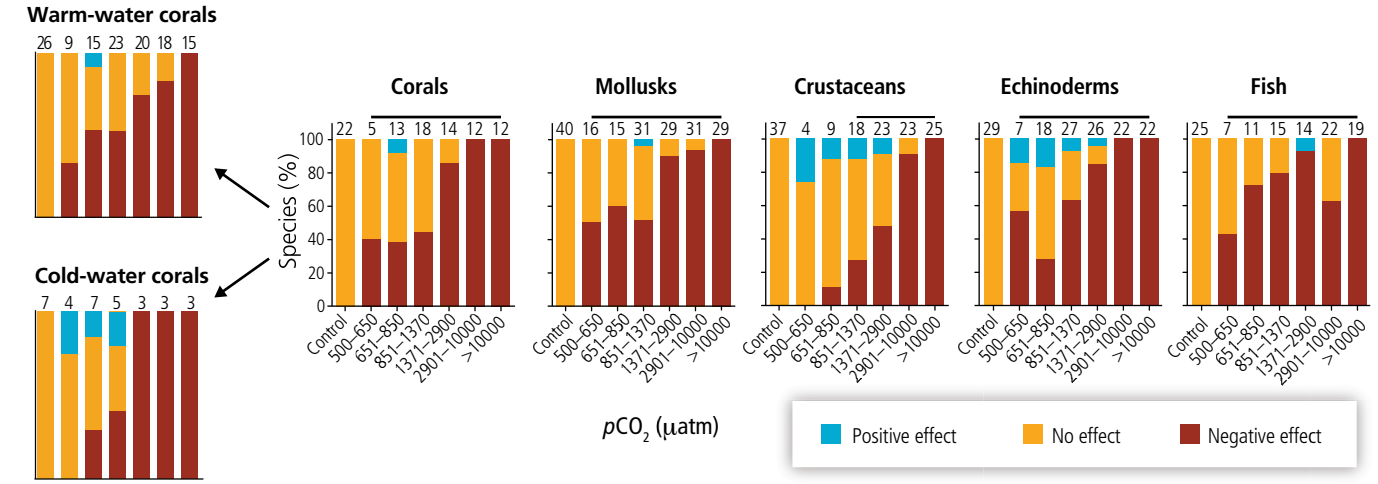
[a]Rather than a sensitivity threshold the entire range of investigated pCO_2 values is given for groups of photosynthetic organisms. In all studies photosynthetic rates are stimulated to different, species-specific degrees by elevated pCO_2, indicating low vulnerability. Coccolithophores and calcifying algae are assessed as being more sensitive than other photosynthetic organisms due to reduced calcification and shell dissolution.

[b]Confidence levels for fishes were converted from medium to low, in light of uncertainty on the long-term persistence of behavioral disturbances.

(a)


Ocean
Epithelia
(gills,gut etc.)
pH and ion regulation
Extracellular space
Intracellular space
Skin, gills
Respiration rate
Shell/skeleton-forming tissue
Calcification rate
Growth
Protein synthesis
Mitochondrial processes
Gene expressions
Blood oxygen transport
Ion-exchange rates
Metabolic rate
Intracellular space
Coccolith vesicle
Coccolith formation
Chloroplast
Animal
Animal cell from, e.g., brain, heart, or muscle
Neural Control
Contraction rate and capacity
Phytoplankter
Coccolithophore

(b)


Warm-water corals
26 9 15 23 20 18 15
Cold-water corals
7 4 7 5 3 3 3
Corals
Mollusks
Crustaceans
Echinoderms
Fish
Species (%)
Control
500–650
651–850
851–1370
1371–2900
2901–10000
>10000
pCO2 (µatm)
Positive effect
No effect
Negative effect

(c)

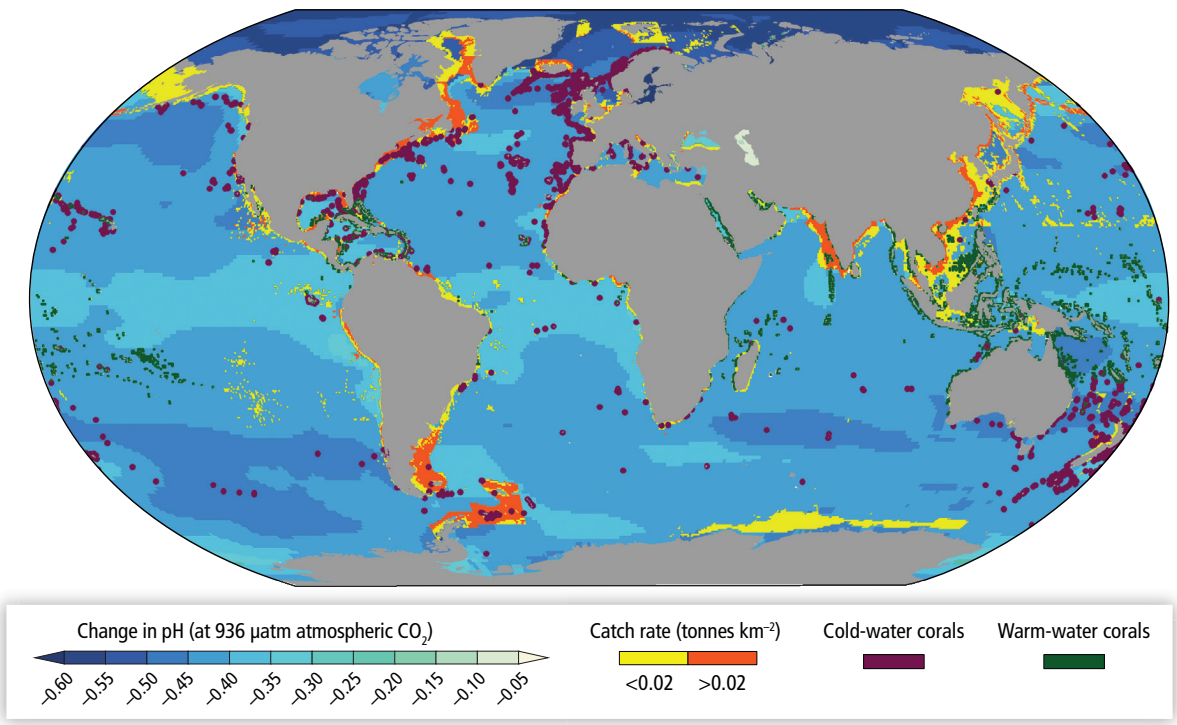

Change in pH (at 936 µatm atmospheric CO2)
-0.60 -0.55 -0.50 -0.45 -0.40 -0.35 -0.30 -0.25 -0.20 -0.15 -0.10 -0.05
Catch rate (tonnes km-2)
<0.02 >0.02
Cold-water corals
Warm-water corals

Figure 6-10 | (a) Responses of a schematized marine animal (left) and a phytoplankter (right) to ocean acidification. Effects are mediated via diffusive CO_2 entry (black arrows) into body and cell compartments, resulting in a rise in pCO_2 (highlighted in red), a drop in compartmental pH (highlighted in blue), and their effects (red arrows) on various processes (red text) in tissues and cellular compartments, as well as on calcium carbonate saturation state (Ω) at calcification sites (after Pörtner, 2008; Taylor et al., 2011). Variable sensitivity relates to the degree of pH decline and compensation, depending on the capacity of pH and ion regulation. (b) Distribution of sensitivities across species within animal phyla, under progressively rising water CO_2 levels, as percent of studied cold- and warm-water coral (mostly scleractinia), echinoderm, molluskan, crustacean, and fish species affected negatively, positively, or not at all (for effects considered, see text). As not all life stages, variables, and pCO_2 ranges were covered in all species, two assumptions partially compensate for missing data: 1) Negative effects at low pCO_2 will remain negative at high pCO_2. 2) A positive or neutral outcome at both low and high pCO_2 will be the same at intermediate pCO_2. As responses reported for each species vary for each pCO_2 range, variable species numbers result (on top of columns). The total number of species studied in a group is shown as the number above the control column. The control category corresponds to 380 μatm. For 2100, RCP scenarios falling within each CO_2 partial pressure (pCO_2) category are as follows: RCP4.5 for 500–650 μatm (approximately equivalent to ppm in the atmosphere), RCP6.0 for 651–850 μatm, and RCP8.5 for 851–1370 μatm. By 2150, RCP8.5 falls within the 1371–2900 μatm category. Horizontal lines above columns represent frequency distributions significantly different from controls (Wittmann and Pörtner, 2013). Data for warm- and cold-water corals as in Table 6-3. (c) Areas with reported annual catches of marine calcifiers (crustaceans and mollusks) ≥ 0.005 tonnes km^{-2} depicted on a global map (weighted mean of the orange color area =0.07 tonnes km^{-2}) showing the distribution of ocean acidification in 2100 according to RCP8.5 (WGI AR5 SPM; pH change from 1986–2005 to 2081–2100) as well as the distribution of warm-water (green dots) and cold-water coral communities (purple dots).

pattern resembles the one seen in the Permian mass extinction (Knoll et al., 2007; Knoll and Fischer, 2011). The picture for fishes is less clear, as the present findings of high vulnerability are not met by similar observations in the fossil record. Evolutionary adaptation may thus eliminate or minimize reported effects.

The capacity for pH and ion regulation and other relevant processes can be upregulated by gene expression, as seen in acclimation studies in echinoderm larvae (O'Donnell et al., 2010; Martin et al., 2011) and fishes (Deigweiher et al., 2008; Tseng et al., 2013), in warm-water coral branches (Kaniewska et al., 2012), but not in a study of warm-water coral larvae (Moya et al., 2012). Few studies address whether and to what extent species undergo evolutionary adaptation to high pCO_2, as seen in the coccolithophore *Emiliania huxleyi* over 500 asexual generations (Lohbeck et al., 2012). In organisms with longer generation times, perturbation studies in the laboratory measure tolerance and acclimation, but not adaptation or natural selection. Animal adaptation is accelerated by high functional variability among larvae, enabling selection of resistant genotypes (*low* to *medium confidence*; Sunday et al., 2011; Parker et al., 2012; Pespeni et al., 2013). This may explain the selective mortality seen in Atlantic cod larvae under elevated CO_2 (Frommel et al., 2012). Both acclimatization and adaptation will shift sensitivity thresholds but the capacity and limits of species to acclimatize or adapt remain largely unknown and hence impacts of acute exposures cannot easily be scaled up to effects on the longer, evolutionary time scales of ocean acidification (Wittmann and Pörtner, 2013). Observations in ecosystems characterized by permanently elevated or fluctuating CO_2 levels, such as upwelling areas, OMZs (Section 6.1.1), or seeps, reflect the existence of sensitivity thresholds (*high confidence*; Section 6.3.2.5) but organisms may have evolved a higher resistance to increased CO_2 levels than elsewhere (*low confidence*).

Table 6-3 compiles effects of ocean acidification observed across taxa in laboratory and field experiments. The latter include studies in mesocosms and at natural analogs, submarine CO_2 venting areas at locales such as Ischia, Italy (Hall-Spencer et al., 2008), Papua New Guinea (Fabricius et al., 2011), and Puerto Morelos, Mexico (Crook et al., 2012). It should be noted that anthropogenic CO_2 accumulation according to RCPs adds to the natural variability of CO_2 concentrations in marine environments. Many groups, especially sessile or non-photosynthetic calcifiers, have sensitive species with vulnerability thresholds surpassed under RCP6.0 by 2100 (*low* to *medium confidence*).

Recent meta-analyses also summarize OA effects, two for biogeochemical processes and relative effect sizes (Harvey et al., 2013; Kroeker et al., 2013), one for the distribution of sensitivity between species within major animal phyla and its change depending on ambient pCO_2 (Figure 6-10; Wittmann and Pörtner, 2013). All of these analyses consider the interaction of warming and CO_2 accumulation (Section 6.3.5). Present limitations in understanding the mechanisms of effect and their long-term persistence compounds accurate projections of the long-term effects of OA (*medium confidence*; Wittmann and Pörtner, 2013).

6.3.2.2. Microbes

The physiology of both calcifying (coccolithophores) and non-calcifying phytoplankton can be influenced by changes in carbonate system variables caused by ocean acidification (Figure 6-10a). Growth and photosynthetic rates of diatoms in laboratory cultures are considered relatively insensitive to elevated CO_2 (Rost et al., 2003; Trimborn et al., 2008). Dinoflagellate sensitivity to elevated CO_2 is poorly studied (Hansen et al., 2007), but in one species carbon fixation rates were enhanced at 750 µatm CO_2 while growth remained unaffected (Fu et al., 2008). Indirect effects of ocean acidification on phytoplankton physiology include altered availability of trace metals needed for many biochemical cycles (Hoffmann et al., 2012).

Harmful algal blooms are a growing problem in coastal waters worldwide (Section 6.4.2.3), and many of the various phytoplankton species that produce bio-accumulated toxins are sensitive to changes in the seawater carbonate buffer system (Hallegraeff, 2010; Fu et al., 2012). For example, the dominance and community structure of harmful bloom dinoflagellates can be profoundly altered by changing pCO_2 (Tatters et al., 2013), and both toxic dinoflagellates and diatoms have been shown to produce higher toxin levels under near-future levels of ocean acidification (Fu et al., 2010; Sun et al., 2011).

Some planktonic N_2-fixing cyanobacteria (diazotrophs), for example, strains (genetically distinct populations of the same species) of offshore cyanobacteria of the genera *Trichodesmium* and *Crocosphaera*, respond to rising CO_2 with increased rates of both carbon and N_2 fixation (Fu et al., 2008; Lomas et al., 2012). In contrast, laboratory studies using the bloom-forming cyanobacteria *Nodularia* (an organism largely found in coastal stratified, eutrophic waters) revealed decreased growth and N_2

fixation under elevated CO_2 conditions (Czerny et al., 2009). The wide range of responses in N_2 fixation (e.g., Hutchins et al., 2007; Levitan et al., 2007; Kranz et al., 2010) may be explained by different CO_2 affinities (i.e., dependences of growth rates on CO_2 concentration) of a range of N_2-fixing cyanobacteria (*Trichodesmium* and *Crocosphaera*) from different oceanic biomes. Some species/strains operate at close to maximum growth rates at present-day oceanic CO_2 levels, whereas others had sub-optimal growth rates under these conditions (Hutchins et al., 2013). To date, the physiological mechanisms underlying these responses remain unknown, especially in open-ocean nitrogen fixers. Cyanobacteria may reallocate energy from their energetically expensive CCMs toward N_2 fixation and the acquisition of growth limiting nutrients (Kranz et al., 2010; Levitan et al., 2010), but evidence for such diversion of energy is lacking. Whether nitrogen fixation will increase with progressive ocean acidification remains to be explored (*low confidence*, *limited* in situ *evidence*, *medium agreement*).

The responses of coccolithophore calcification to OA are species specific and highly variable. The function(s) of calcification are not well understood, making it difficult to evaluate the consequences of lowered calcification (e.g., Rost et al., 2008). Reductions, increases, and unchanged calcification rates (and shell structure) have all been found in different coccolithophore species for RCP8.5 CO_2 conditions projected around 2100 (Riebesell et al., 2000; Zondervan et al., 2001; Langer et al., 2006; Iglesias-Rodriguez et al., 2008). Calcification in coccolithophores is species (Langer et al., 2006) and in *Emiliania huxleyi* even strain specific (Langer et al., 2009, 2011; Hoppe et al., 2011). It thus remains unclear whether OA will result in exoskeletons that are insufficiently calcified for sustained structural support and protection in coccolithophores (*medium evidence*, *low agreement*).

Foraminifera display decreasing calcification and shell weight under elevated CO_2 (Lombard et al., 2010). Changes in historical specimens (Moy et al., 2009; see Section 6.3.2.5.1) and during glacial-interglacial cycles (Barker and Elderfield, 2002) support projections of future reductions in net calcification by foraminifera (*medium* to *high confidence*).

6.3.2.3. Macroalgae and Seagrasses

Primary production, shoot density, reproductive output, and below-ground biomass of seagrasses generally respond positively to elevated pCO_2, indicating CO_2 limitation of their productivity. Such effects were identified in both laboratory and field above 720 to 1800 µatm (*high confidence*; e.g., Palacios and Zimmerman, 2007; Hall-Spencer et al., 2008; Andersson et al., 2011; cf. Section 5.4.2.3). Production, growth, and recruitment of most but not all non-calcifying seaweeds also increased at CO_2 levels from 700 to 900 µatm (RCP8.5; Porzio et al., 2011; Kroeker et al., 2013). Some non-calcifying seaweeds and seagrasses will thus benefit from future ocean acidification (*high confidence*) but OA exposes them to higher than usual grazing as a consequence of losing deterrent phenolic substances (*low confidence*; Arnold et al., 2012).

Calcifying algae (corallines) show complex and species-specific responses of photosynthesis to elevated CO_2, but calcification is impacted once species-specific pCO_2 thresholds are surpassed (*medium confidence*; Anthony et al., 2008; Martin and Gattuso, 2009). At habitat temperature calcification by temperate coralline red and calcareous green algae increased at CO_2 levels up to 900 µatm and decreased only at the highest concentration applied (2850 µatm), but did not fall below rates found at present-day pCO_2 (Ries et al., 2009). During 3 months of exposure, growth of *Lithothamnion glaciale*, a cold-water calcareous red alga, decreased progressively with rising CO_2 levels, and its structural integrity was weakened beyond 590 µatm (Ragazzola et al., 2012), potentially influencing ecosystem function. Some calcifying algae may thus be impacted by future ocean acidification (*medium confidence*).

6.3.2.4. Animals

Studies of marine animals and their life stages show a high diversity and variability of processes affected by ocean acidification. Many variables studied reflect physiological performance (O_2 consumption, exercise, behavior, calcification, growth, immune response, acid-base balance, gene expression, fertilization, sperm motility, developmental time, production of viable offspring, and morphology; Table 6-3; Figure 6-10). In some species growth may be stimulated by OA, in others depressed or unaffected (cf. Gooding et al., 2009; Munday et al., 2009a, 2011a; Dupont et al., 2010). The degree of CO_2-induced acidosis and its compensation by ion exchange may shape sensitivity (Section 6.3.2.1). Full exploitation of the ability to resist pCO_2 increases depends on the availability and high quality of food and the strengthening of fitness (Gooding et al., 2009; Melzner et al., 2011). However, food quality of prey organisms may decrease under elevated pCO_2. For example, slower reproduction and growth of the copepod *Acartia tonsa* under 760 µatm pCO_2 was related to the decreasing quality of its diatom food (Rossoll et al., 2012).

Changes in calcification rates reported from CO_2 manipulation experiments vary widely. Reduced calcification and weakened calcified structures were seen under elevated pCO_2 in corals (see Section 6.3.2.4.2), echinoderms (Kurihara and Shirayama, 2004), mollusks (Gazeau et al., 2013), and larval crustaceans (Arnold et al., 2009; Walther et al., 2011). Some adult limpets and urchins increased calcification rates at pCO_2 from 600 to 900 µatm, before it fell at even higher pCO_2. In some adult crabs, lobsters, and shrimps calcification rates increased further with rising pCO_2 (Ries et al., 2009). Stronger internal structures such as cuttlebones and otoliths resulted from enhanced calcification under elevated pCO_2 in juvenile cuttlefish (cephalopods: Gutowska et al., 2008) and fishes (Checkley, Jr. et al., 2009; Munday et al., 2011b), with unclear impacts on fitness. Energy costs in epithelia or calcification compartments may be enhanced by elevated pCO_2 causing a stimulation of metabolism (Section 6.3.2.1). In some cases, this may indicate imbalances in energy budget rather than increased CO_2 resistance, for example, if costs are down-regulated in muscle or liver. Enhanced calcification can then occur at the expense of growth (*medium confidence*; Wood et al., 2008; Beniash et al., 2010; Thomsen and Melzner, 2010; Parker et al., 2011).

Studies on calcifying zooplankton focused on pteropods (planktonic mollusks with aragonite shells). These form an integral part of the food web, both as grazers and prey, for example, for pink salmon (Armstrong et al., 2005; Hunt et al., 2008). In the Sub-Arctic, the Arctic, and the Southern Ocean, pteropods will reduce calcification in response to OA

until at least the end of the century (*medium confidence*; Orr et al., 2005; Comeau et al., 2009; Lischka et al., 2011).

Elevated CO_2 causes behavioral disturbances in fishes (studied mostly in larvae and juveniles; Munday et al., 2010; Ferrari et al., 2011; Domenici et al., 2012; Jutfeld et al., 2013) through neural mechanisms (Nilsson et al., 2012). The long-term persistence and evolutionary relevance of these behavioral effects need further study before general conclusions can be drawn (*low confidence*; Wittmann and Pörtner, 2013; see also Table 6-3).

6.3.2.4.1. Animal life cycles

It is generally held that organisms at early life stages are always more sensitive to environmental stress than adults. In the context of ocean acidification this statement is supported by findings like larval oyster fatalities in aquaculture caused by upwelled CO_2-rich waters (*high confidence*; Barton et al., 2012). A key aspect may also be that larvae growing or developing more slowly under elevated CO_2 as in various groups including fishes (Baumann et al., 2012; see also Section 6.3.2.1) may encounter enhanced mortalities due to prolonged predator exposure. Comparative studies of animal sensitivities to OA over a complete life cycle or during critical transition phases (e.g., fertilization, egg development and hatching, metamorphosis, molting) are scarce and do not support generalized conclusions (*low confidence*).

Effects of elevated CO_2 on one life stage or transition phase may affect or carry over to the next one. Molting success into the final larval stage was reduced in a crab species (Walther et al., 2010). In a sea urchin species, negative impact was found to accumulate during 4 months acclimation of adults reducing reproductive success. This impact was, however, compensated for during extended acclimation of female urchins for 16 months (Dupont et al., 2013). Negative impact was still transferred from urchin larvae to juveniles under elevated pCO_2. Conversely, adult oysters acclimated to high CO_2 acquired resistance which was carried over to their offspring (Parker et al., 2012). More long-term acclimation studies to realistic emission scenarios are needed for generalized conclusions. Furthermore, the preposition that juvenile life stages are always more sensitive than adults needs thorough re-investigation in the context of ocean acidification, especially in the context of the notion that larvae may provide a selection pool for survival of the most suitable phenotypes (*low confidence*; Section 6.3.2.1).

6.3.2.4.2. Warm- and cold-water coral communities

In warm-water reef-building corals, OA causes genus-specific reductions in calcification (Leclercq et al., 2002; Langdon and Atkinson, 2005; Kleypas and Langdon, 2006). Nutrient availability to symbionts may sustain calcification. Heterotrophic feeding by the corals also supports energy-dependent calcification and acid-base regulation, and thus resilience (Edmunds, 2011; Figure 6-10). Females may sacrifice calcification more than males due to energetic trade-offs with reproduction (Holcomb et al., 2012). Warm-water corals are thus sensitive to future OA (*high confidence*; Table 6-3).

The cold-water coral *Lophelia pertusa* shows resilience to ocean acidification. In short-term ship-board incubations pH reductions between 0.15 and 0.3 units (540 and 790 µatm) led to calcification rates reduced by 30 to 56% (Maier et al., 2009), especially in young, fast growing polyps. However, net calcification was maintained at seawater aragonite saturation <1. Exposure to a pCO_2-induced pH reduction by 0.1 units or even to the projected end of century pCO_2 of 930 µatm led to calcification rates being maintained over 6 to 9 months (Form and Riebesell, 2012; Maier et al., 2013). This ability is probably due to a regulated upward shift of pH and carbonate saturation at organismal calcification sites (McCulloch et al., 2012; see also Figure 6-10). Natural distribution of other cold-water species covers wide natural pH gradients in Chilean fjords (*Desmophyllum dianthus*; Jantzen et al., 2013) and ranges into waters with undersaturated carbonates as in Australian waters (four scleractinian corals; Thresher et al., 2011). Pre-adaption to elevated pCO_2 apparently exists; however, species vulnerabilities to further increases in pCO_2 have not been investigated. Again, vulnerability is species specific, colonial scleractinians may be limited to water saturated or near-saturated with aragonite, whereas others are not (Thresher et al., 2011). Conclusions on the relative vulnerability of the group appear premature (Table 6-3). To what extent a further lowering of carbonate saturation values will influence the future distribution of various calcite or aragonite forming cold-water corals is not clear (*low confidence*; Guinotte et al., 2006).

6.3.2.5. Ecosystems

For insight into ecosystem level processes, laboratory studies have been supplemented with experimental studies in large volume mesocosms (i.e., >1000 L) and in the field, and with long-term field observations. Together they inform the debate over the attribution of field observations to ocean acidification.

6.3.2.5.1. Evidence from field observations

Contributions of anthropogenic ocean acidification to climate-induced alterations in the field have rarely been established and are limited to observations in individual species (see also Section 30.5.1.1.3). Shell thinning in modern planktonic foraminifera (collected 1997–2004) in the Southern Ocean compared to those from the Holocene and before was attributed to anthropogenic ocean acidification (Moy et al., 2009). Both anthropogenic OA and the upwelling of CO_2-rich deep waters (Section 30.5.4.1.4) were held responsible for shell thinning in planktonic foraminifera in the Arabian Sea over the last century (de Moel et al., 2009) or in live pteropods collected in 2008 in the Southern Ocean (*medium evidence*, *medium agreement*; Bednaršek et al., 2012). However, no changes were observed in a 57-year record of the composition and abundance of calcifying zooplankton in the increasingly acidified California Current System (Ohman et al., 2009). Possible explanations for the absence of significant responses in some studies include insufficient lengths of time series (Section 6.1.2), organisms being pre-adapted to naturally high CO_2 in upwelling or other systems, linked to a low signal-to-noise ratio, or the difficulty of detecting small OA effects in comparison with larger ecosystem effects of other drivers such as temperature, for example, in calcifying plankton (Beaugrand et

al., 2013). Similarly, declines in coral calcification and performance in the field (De'ath et al., 2009) were attributed to thermal extremes, but may also include an as-yet unclear contribution from OA.

6.3.2.5.2. Microbial communities and nutrient cycles

Laboratory experiments, coastal mesocosm studies (Weinbauer et al., 2011), and field experiments (Beman et al., 2011; Law et al., 2012) have yielded various, sometimes conflicting, results on the effects of CO_2 on microbial processes. From a meta-analysis of available data, Liu et al. (2010) conclude that the rates of several microbial processes will be affected by OA, some positively, others negatively. The potential of the microbial community to adapt to ocean acidification and maintain functionality, either by genetic change at the species level or through the replacement of sensitive species or groups at the community level, remains to be explored further. At the present time there is insufficient field-based evidence to conclude that elevated CO_2 will affect natural assemblages of microorganisms (*limited evidence*, *low agreement*) with the possible exception of the negative impact on calcification (Joint et al., 2011).

Experimental studies on OA effects (through reduced pH or increased CO_2) on autotrophic and heterotrophic microbial production have provided inconsistent results. Microbes are characterized by large diversity and broad environmental adaptation, and hence may respond to environmental challenges by exploiting such diversity via species replacements (Krause et al., 2012). This makes it difficult to project the findings of laboratory experiments investigating the response of microbes to OA to the ecosystem level. Relevant variables include cellular elemental stoichiometry (C:N:P ratios; Riebesell, 2004; Fu et al., 2007), rates of CO_2 and N_2 fixation (Riebesell, 2004; Hutchins et al., 2007, 2009), rates of nitrification (Beman et al., 2011), changes in the proportion of dissolved organic carbon (i.e., DOC) to particulate photosynthate produced during carbon fixation (Kim et al., 2011), and the response of viruses (Danovaro et al., 2011).

Field experiments led to the projection that nitrification rates (ammonia oxidation to nitrite and nitrite oxidation to nitrate) of bacteria and archaea will be reduced by 3 to 44% when pH is reduced by 0.05 to 0.14 (Beman et al., 2011), corresponding to a mean rise in CO_2 by approximately 100 µatm. The reported decrease in nitrification occurred regardless of natural pH variability, providing no evidence for acclimation of the nitrifiers to reduced pH, for example, in upwelling areas. Potential changes in microbial cell abundance, possibly as a result of lower cellular nitrification rates, could further decrease the total rate of nitrification.

It remains unclear whether OA has contributed to the systematic changes in phytoplankton abundance and community structure observed over recent decades, which have largely been attributed to warming (Chavez et al., 2011). In natural assemblages from coastal and polar waters, NPP is stimulated by increased CO_2 (*medium confidence*; Riebesell et al., 2008; Tortell et al., 2008). Small differences in CO_2 sensitivity may lead to pronounced shifts in the dominance of species (Tortell et al., 2008; Beaufort et al., 2011). Quantification of the calcite mass of the coccolithophore community in the present ocean and over the last 40 kyr were in large part attributed to shifts between differently calcified species and morphotypes according to carbonate chemistry (Beaufort et al., 2011). The same study, however, also observed heavily calcified *Emiliania huxleyi* morphotypes in upwelling systems characterized by low pH, a finding which highlights the complexity of assemblage-level responses and may indicate pre-adaptation to elevated pCO_2. Owing to the complex response patterns, it is not possible to project ecosystem-level effects from effects on coccolithophore calcification in monospecific culture experiments (*low confidence*). Projections of OA impacts on phytoplankton become even more complicated by synergistic interactions with other drivers (Boyd, 2011; see also Section 6.3.5).

6.3.2.5.3. Macrophytes and macrofauna

Macrofauna and macrophyte communities have been studied in mesocosms and in ecosystems exposed to shifted upwelling regimes or at natural volcanic CO_2 vents (Fabricius et al., 2011; Kroeker et al., 2011). The latter are considered as natural analogs of future ocean acidification. An 8-year trend of (variable) pH decline in upwelled waters along the Northeast Pacific coast was paralleled by shifts in community composition, where shelled species like mussels were replaced by fleshy algae and barnacles (Wootton et al., 2008). Macrofaunal calcifiers at CO_2 vents (Hall-Spencer et al., 2008; Fabricius et al., 2011) and in mesocoms (Christen et al., 2013) display a lowering of species richness. These findings suggest that non-calcifiers increasingly outcompete calcifiers once pH_T decreases to a mean of 7.8 to 7.7 (*medium confidence*). Finally, a loss of calcifiers from mesocosms occurred around 0.5 units below the pH values expected from OA under RCP8.5 by 2100 (*medium confidence*; Christen et al., 2013). At CO_2 seeps, calcitic bryozoans replace coralline algae, which have more soluble high-calcite skeletons (Martin et al., 2008). Seagrasses and non-calcifying algae gain a competitive advantage (Fabricius et al., 2011). Coral communities exposed to high pCO_2 waters (from upwelling or seeps) have lower growth, calcification, and biodiversity (Manzello et al., 2008; Fabricius et al., 2011), resulting in a shift from net accretion to erosion (Box CC-CR). The use of seeps as analogs of future OA is limited as pH variability is high at these sites, such that effective values may be lower than indicated by the average change (Hall-Spencer et al., 2008; Porzio et al., 2011). During periods of high pH at the seeps, they are recolonized by invertebrates and fishes from neighboring areas with normal pH, compromising assessments of long-term sensitivity thresholds. Overall, findings available from mesocosms and natural analogs indicate losses in diversity, biomass, and trophic complexity of benthic marine communities due to elevated CO_2 (*high confidence*) and support the projection of similar shifts in other systems with continued OA (*medium confidence*).

Enhanced freshwater input by poorly buffered rivers or by precipitation, into estuaries, brackish oceans like the Baltic (Section 30.5.3.1.4), and into freshening polar oceans, reduces salinity and alkalinity at rising atmospheric pCO_2 and thereby, alters the carbonate system and enhances OA (Section 6.1.1). Estuaries usually have OMZs, where background pCO_2 is elevated. Its reduction by dilution causes the acidification effect to be somewhat less. Enhanced pH reduction and variability in hyposaline waters may constrain the distribution of sensitive species further (*low confidence*; Miller et al., 2009; Denman et al., 2011).

6.3.2.5.4. Conclusions

Natural analogs and laboratory and mesocosm experiments provide evidence for differential effects of ocean acidification on species and communities. Sensitivity to OA is species specific (*high confidence*); differential sensitivities and associated shifts in performance and distribution will change predator-prey relationships and competitive interactions (*low* to *medium confidence*). OA may stimulate global net primary production (*low confidence*) and nitrogen fixation (*medium confidence*). OA will increase the abundance and primary production of non-calcifying macrophytes, but will be harmful to calcifying algae and many heterotrophs (*medium confidence*). Ecosystems relying on calcified structures and at risk of dissolution under OA include warm-water coral reefs (*high confidence*) and their cold-water equivalent (*medium confidence*). Further studies need to explore how OA may change the composition of communities, impact food webs, and affect higher trophic levels.

6.3.3. Life in Hypoxia and Anoxia

6.3.3.1. Principles

Hypoxia constrains organisms which rely on aerobic metabolism (Section 6.1.1; FAQ 6.2). Below O_2 concentrations of 60 µmol kg^{-1}, commonly termed hypoxic (Section 6.1.1.3), communities undergo species losses and replacements and are transformed into communities with species showing characteristic hypoxia adaptations. However, O_2 can limit animal life at even higher levels, just below air saturation (Gilly et al., 2013). Organisms' tolerance thresholds have been defined by either the critical O_2 partial pressure (P_c) or concentration (O_2crit). Thresholds vary across domains and are highest for large multicellular organisms. Among these, the P_c at rest varies depending on species, body size, and life stage. In animals below the P_c aerobic metabolic rate fails to be maintained and anaerobic metabolism contributes to energy production (Pörtner and Grieshaber, 1993). The critical oxygen threshold is set by the capacity of ventilatory and circulatory systems to supply O_2 and cover demand. The threshold increases once metabolism is stimulated by muscular activity, temperature, or food uptake (Pörtner, 2002a; Ekau et al., 2010; Seibel, 2011; see also Figure 6-11). At extreme temperatures, O_2crit approaches the oxygen content of air-saturated water (Pörtner, 2010; McBryan et al., 2013), indicating high sensitivity to hypoxia in the warmth. Most animals can only sustain anaerobic metabolism temporarily, even if they are energy efficient and survive long periods of anoxia (Grieshaber et al., 1994). Such time-limited tolerance is higher in large than in small individuals or larvae, related to the higher capacity of anaerobic metabolism in large specimens (Gray et al., 2002; Jessen et al., 2009).

6.3.3.2. Microbes

Bacteria and protists consume ambient oxygen down to very low levels in oxygen minimum zones and sustain OMZs by their metabolic diversity (Figure 6-11; WGI AR5 Section 3.8.3). OMZs form habitat for both anaerobic and aerobic microbes that can utilize very low (<1 µmol kg^{-1}) O_2 concentrations (Stolper et al., 2010). Hypoxia is paralleled by elevated pCO_2 and enhanced acidification. Expanding OMZs will select for the proliferation of spezialized microbes (*high confidence*).

6.3.3.3. Animals and Plants

In mesopelagic OMZs, zooplankton also contribute to the development of hypoxia (Robinson et al., 2010; see also FAQ 6.2). During daytime zooplankton congregate at the upper margin of OMZs, where the degradation of organic material causes intensified respiration and oxygen depletion (Bianchi et al., 2013). Animals living permanently in the OMZ still cover virtually all energy demand by aerobic metabolism. This requires special adaptations leading to a reduction in O_2 and energy demand, and the improved ability to use available O_2 efficiently. Enhanced hypoxia tolerance reflected in low O_2crit values is supported by small body size and by cold temperature (Vetter et al., 1994; Pörtner, 2002b; Levin et al., 2009). Accordingly, low O_2 levels support abundant meiofauna (very small fauna, <1 mm) that benefit from abundant food and reduced predation by larger organisms (Levin, 2003). Under suboxia only specialists can survive (Vaquer-Sunyer and Duarte, 2008). Expansion of suboxic and anoxic centres of pelagic OMZs and benthic dead zones will lead to loss of habitat for animal life (*high confidence*).

Large, more active animals such as fishes, crustaceans, and muscular (as opposed to ammoniacal) squids tend to have high O_2 demands associated with high O_2crit thresholds, and are therefore excluded from permanently hypoxic water bodies. However, even in high-activity animal groups some specialists such as Humboldt squid or bigeye tuna have adapted to enter hypoxic environments though only temporarily (Richards et al., 2009; Seibel, 2011). The time-limited tolerance of animals to hypoxia below the O_2crit is maximized by the depression of energy demand, for example, during periods of metabolic arrest (e.g., developmental arrest or diapause of copepods; Auel et al., 2005). Hypoxia-adapted lifeforms will benefit from expanding OMZs (*high confidence*).

There is little information on the hypoxia sensitivity of macrophytes or their O_2crit values. In eelgrass (*Zostera marina*), warming causes the hypoxia threshold to rise due to a strong increase in tissue respiration. Concomitant water or sediment hypoxia can elicit tissue anoxia and sudden die-offs (Raun and Borum, 2013). By contrast, macroalgae attached to rocks rarely encounter anoxia (Raven and Scrimgeour, 1997). Expanding benthic OMZs will constrain the distribution of macrophytes (*medium confidence*).

6.3.3.4. Ecosystems

OMZs, shoaling, and expanding vertically and laterally (Gilly et al., 2013) will cause habitat and abundance losses for intolerant taxa such as mesopelagic (Koslow et al., 2011) and epipelagic fishes with a high O_2 demand (*medium confidence*; Prince et al., 2010; Stramma et al., 2012; see also FAQ 6.2). In line with the distribution of hypoxia sensitivities (Figure 6-11; Sections 6.3.3.1, 6.3.3.3), expanding OMZs will further constrain the distribution of key zooplankton and nekton species and influence their diurnal and ontogenetic vertical migrations (*medium confidence*; Ekau et al., 2010). The composition of microbial and faunal pelagic communities will shift from diverse mid-water assemblages to

migrant biota that return to oxygenated surface waters at night (Seibel, 2011). Dissolved O_2, among other factors, plays an important role in shaping large alternating fluctuations of sardine and anchovy abundances, particularly off Peru. Anchovies are not strongly affected by a shallow oxycline (<10 m), while sardines actively avoid such conditions (Bertrand et al., 2010). Where OMZs intersect the continential shelves, groundfishes (McClatchie et al., 2010) and large benthic invertebrates such as crabs display high mortalities (Chan et al., 2008). Susceptibility of early life stages to hypoxia in both pelagic and benthic ecosystems (Ekau et al., 2010) threatens population survival. Effects of hypoxia propagate along the food chain, constraining fish stocks and top predators (*high confidence*; Stramma et al., 2010). Hypoxia reduces biodiversity (Levin et al., 2009; Gooday et al., 2010) and causes the marginalization of calcifiers, due to low metabolic rates and high pCO_2 (*high confidence*; Levin, 2003; Levin et al., 2009).

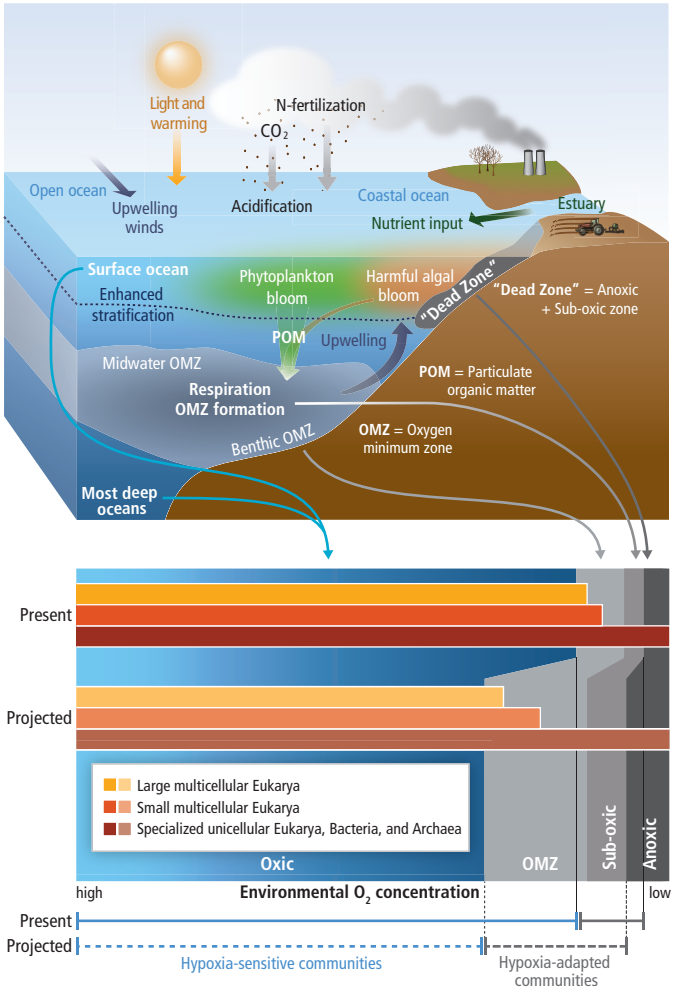


Figure 6-11 | (a) Principal mechanisms underlying the formation of hypoxic conditions and their biological background (modified from Levin et al., 2009; Levin and Sibuet, 2012). The buoyancy flux from fluvial discharges produces sharp density stratification at the base of the freshened layer (also valid for ice melt and high precipitation) near the surface and, hence, vertical mixing is greatly reduced. In consequence, the nutrient inputs from the river and the atmosphere accumulate in a narrow upper layer, leading to blooms of phytoplankton, possibly including harmful algae. The enhancement of oxygen consumption due to aerobic decomposition of sinking particulate organic matter (POM) results in hypoxic conditions of benthic and mid-water oxygen minimum zones (OMZs). Enrichment of nutrients (eutrophication) results in coastal dead zones. In the open oceans, heating of the upper layer increases stratification, while the wind-driven upwelling of hypoxic, nutrient-rich water from deeper layers adds to the formation of the OMZs (Box CC-UP). (b) Distribution of free-living marine organisms (microbes such as archaea, bacteria, protists, small and large multicellular animals, and plants) across the ranges of O_2 concentrations in various water layers. Hypoxia tolerance is enhanced in small compared to large organisms, allowing unicellular species and small animals to thrive in extremely hypoxic habitats. Species richness and body size of animals decrease with falling O_2 levels.

The expansion and enhanced variability of OMZs increases dissimilatory nitrate reduction and anaerobic ammonium oxidation (anammox), both releasing N_2 into the atmosphere, reducing the availability of fixed nitrogen, and limiting oceanic primary productivity (*medium confidence*). Water column denitrification and N_2 fixation are spatially and temporally variable (*limited evidence*, *low confidence*), suggesting that climate effects on these processes are unlikely to operate uniformly (Brandes et al., 2007; Fernandez et al., 2011; Franz et al., 2012).

If O_2 levels decline and OMZs expand, tolerant taxa, such as anaerobic bacteria (Ulloa et al., 2012), gelatinous zooplankton (medusae, ctenophores), selected fishes (gobies, hake), and possibly selected cephalopods (Gilly et al., 2006; Bazzino et al., 2010) will respond with range expansions or population growth. Similar phenomena are expected with intensified upwelling causing extensive mortalities of coastal fishes and invertebrates (Box CC-UP). A community change toward hypoxia-tolerant fauna will occur in mid-water (*high confidence*). The diversity of macroorganisms will decrease and, finally, higher marine organisms will disappear and heterotrophic microorganisms will dominate (*high confidence*). In isolated water bodies such as the Black Sea, warming will lead to the expansion of anoxia and hydrogen sulphide (H_2S) poisoning, reduce pelagic and bottom faunal distributions, and shape trophic relations, energy flows, and productivity (Daskalov, 2003; Fashchuk, 2011).

6.3.4. Mixed Layer Depth and Light Shaping Net Primary Production

The upper ocean is characterized by physical and chemical gradients in the surface mixed layer that influence the magnitude of photosynthetic carbon fixation, often termed net primary production (NPP). The availability of light and nutrients to photoautotrophs sets daily rates of NPP and may be altered directly or indirectly, through changing mixed layer depths, shifts in the circulation regime at different spatial scales, and the physical displacement of organisms (Section 6.1.1.4; Box CC-PP; Figure 6-2). A changing climate will affect mixed layer depth, cloudiness, and/or sea ice areal extent and thickness and thereby modulate NPP (*high confidence*). A stronger vertical density gradient will reduce the communication between the sunlit upper ocean where photosynthesis takes place and the underlying nutrient-rich waters (Figure 6-2). The supplies of plant nutrients (macro-nutrients) such as nitrate, and of micro-nutrients such as iron (Pitchford and Brindley, 1999) vary seasonally (Boyd, 2002) and regionally (Moore et al., 2002), such that NPP may be simultaneously limited (co-limited) by more than one resource (Saito et al., 2008; see also Section 6.3.5).

The changing range and intensity of underwater light will lead to changes in NPP as well as in phytoplankton community composition (Doney, 2006; Boyd et al., 2010). The response of phytoplankton to

changing sunlight involves photo-physiological acclimation via changes in cellular chlorophyll, but such acclimation is constrained by unidentified limits (Falkowski and Raven, 1997). A longer growing season, with more sea ice-free days between 1998 and 2009, may have increased NPP in open Arctic waters (Arrigo and van Dijken, 2011; see also Box CC-PP), complemented by massive under-ice blooms as seen in 2011, favored by light that penetrates surface melt ponds and thinner, for example, first-year ice (Arrigo et al., 2012). There are also reports of increased incidences of high phytoplankton stocks, and hence of greater NPP, deeper in the water column (i.e., where it cannot be detected by satellite) during summer in the Arctic, which have implications to assessing changes in NPP from space (Hill et al., 2013). Little is known about shifts from sea ice algae to free-drifting phytoplankton expected with a decrease in sea ice cover and effects of increased light in polar waters in the coming decades (*low confidence*). In the Arctic, summer ice melt led to a rapid export of sea-ice algae to the deep ocean (Boetius et al., 2013). As some krill feed primarily on sea ice algae, it is unclear (*low confidence*) whether they will adapt to feeding mainly on free-drifting phytoplankton (Smetacek and Nichol, 2005).

A range of time series observations, from *in situ* phytoplankton abundances to satellite remote sensing, have been used to assess whether phytoplankton stocks and hence rates of NPP have altered over recent decades. Increases in phytoplankton stocks were found in regions where colder waters had warmed in the Northeast Atlantic, whereas the opposite trend was observed for warm-water regions from a phytoplankton abundance time series (Richardson and Schoeman, 2004). Lower chlorophyll concentrations at warmer SSTs in nutrient-poor low-latitude waters, based on satellite ocean color data, have been interpreted as an effect of increased stratification on phytoplankton stocks. It has thus been suggested that expanding, permanently stratified, low-chlorophyll, tropical regions (WGI AR5 Chapter 3) indicate declining phytoplankton stocks in the warming oligotrophic waters of the North and South Pacific and North and South Atlantic (*limited evidence*, *low agreement* due to methodological uncertainties; Box CC-PP; Polovina et al., 2008; Signorini and McClain, 2012; see also Section 30.5.1.1.2). Furthermore, a transition to conditions favoring increased frequency or even permanence of El Niño in a warmer future (Wara et al., 2005) and further expansion of subtropical ocean gyres (Polovina et al., 2008; see also Section 30.5.6) may lead to lower global ocean NPP (*low* to *medium confidence*).

However, these long-term "blended" projections (i.e., constructing a biomass time series using multiple proxies such as ocean transparency) of a global decrease in phytoplankton biomass (Boyce et al., 2010) have been refuted (Mackas, 2011; McQuatters-Gollop et al., 2011; Rykaczewski and Dunne, 2011). Time series shorter than 20 years do not resolve impacts of bi-decadal variation such as the Pacific Decadal Oscillation or the lunar nodal cycle (e.g., Watanabe et al., 2008; Henson et al., 2010). Analysis of continental shelf ecosystems, including field data in the most productive upwelling areas covering the last 20 years (e.g., Chavez et al., 2011), revealed a large variety of trends at scales of several decades but a general increase in NPP on most shelves (Sherman and Hempel, 2009; Bode et al., 2011), possibly caused by natural climate variability, anthropogenic climate change, and/or anthropogenic eutrophication. Recent field measurements document increasing quantities of both anthropogenic fixed N (Duce et al., 2008) and biologically fixed atmospheric nitrogen (Mouriño-Carballido et al., 2011) entering the open ocean, which could lead to increased NPP especially in warm, stratified tropical and subtropical oceans provided sufficient phosphate and other growth requirements are present (*low confidence*; e.g., Sohm et al., 2011).

For heterotrophs, from bacteria to fish, mammals, and birds, the uptake of organic material as food, ultimately provided by NPP, is central not only to productivity but also for fueling energy-consuming functions including the resistance of organisms to environmental change and pathogens (Sections 6.3.1-2). Any direct influence of climate on the abundance and quality of feed organisms will thus translate to indirect effects on the productivity and well-being of foraging animals (*high confidence*; Figures 6-5a, 6-7a, 6-12).

Overall, pelagic systems respond to climate change by region-specific changes in productivity with the projection of a small net reduction in global ocean NPP by 2100 (*medium confidence*; Box CC-PP). The spatial reorganization of NPP between latitudes affects higher trophic levels by alteration of the composition and functioning of pelagic communities (*medium confidence*).

6.3.5. Concurrent Responses to Multiple Drivers

Climate change alters oceanic properties globally, with concurrent changes in temperature, dissolved CO_2 and O_2, light, and nutrient concentrations (e.g., Sarmiento et al., 1998; Matear and Hirst, 1999; Boyd and Doney, 2002; Ekau et al., 2010; see also Figure 6-2). Additional direct human interventions at regional scale comprise the introduction of non-native species, overfishing, pollution, long-range atmospheric transport of nitrogen, point-source eutrophication, and habitat destruction (Carlton, 2000; Boyd and Hutchins, 2012). Worldwide alterations in marine ecosystems (Pauly et al., 1998; Österblom et al., 2007) have been linked to direct human activities, especially fishing (Frank et al., 2005; deYoung et al., 2008; Casini et al., 2009), but may also be caused to some extent by climate variability and change (Cheung et al., 2013a).

Alteration of each individual property has pronounced effects on organisms from microbes to animals, and hence on ecosystems (Sections 6.3.1-4). The cumulative effects of these factors will result in complex patterns of change, from organismal physiology to the areal extent and boundaries of biogeographic regions (Table 6-4). In many organisms, effects of ocean acidification interact with those of other key drivers such as temperature and hypoxia (Boyd, 2011; Gruber, 2011; Pörtner, 2012) and translate from molecular to ecosystem level impacts. In phytoplankton, low light (Zondervan et al., 2002) or nitrogen limitation (Sciandra et al., 2003) limit beneficial OA effects on photosynthesis and have a strong negative effect on plankton calcification (Rokitta and Rost, 2012). Nutrients and light support functional adjustments to OA through gene expression changes (Dyhrman et al., 2006; Richier et al., 2009).

Similar to today, paleo-events such as the Palaeocene-Eocene Boundary demonstrate concurrent warming, enhanced stratification of the oceans, deoxygenation of deeper waters, and OA, albeit at a rate more than 10 times slower than today's rate (Section 6.1.2). Both the complexity of paleo-ecosystem changes and the complexity of present effects confound

the clear attribution of biological trends to individual drivers (Parmesan et al., 2011). For warming and hypoxia, changes are accelerated by effects of shifting seasonal or even diurnal extremes and their frequency on organisms and ecosystems (*medium evidence*, *medium agreement*) (e.g., Pörtner and Knust, 2007; Díaz and Rosenberg, 2008). This may also apply to effects of anthropogenic OA (*limited evidence*, *low agreement*).

6.3.5.1. Principles

Effects of various climate drivers on ocean ecosystems are intertwined and effects may be exacerbated by responses of biota. For example, warming reduces O_2 solubility and enhances biotic O_2 demand, which exacerbates hypoxia, produces CO_2, and causes acidification (Millero, 1995; Brewer and Peltzer, 2009). Drivers act with either additive, synergistic (i.e., amplification of) or antagonistic (i.e., diminution of) effects. A meta-analysis of 171 experimental studies that exposed marine systems to two or more drivers identified cumulative effects that were additive (26%), synergistic (36%), or antagonistic (38%) (Crain et al., 2008). Effects range from direct impacts of ocean warming on organismal physiology (Pörtner and Knust, 2007) to ocean acidification acting together with warming, for example, on coccolithophore calcite production and abundances (Feng et al., 2009), or with hypoxia and/or salinity changes (Table 6-4). Interactions of predominantly temperature, ocean acidification, and hypoxia have *likely* been involved in climate-driven evolutionary crises during Earth history (Pörtner et al., 2005; see also Section 6.1.2).

Effects on individual organisms may also reflect intertwined impacts of ocean warming, acidification, and hypoxia, which may operate through interrelated functional principles (Pörtner, 2012). Such knowledge helps to reconcile apparently contrasting findings. For example, warming toward the thermal optimum (Figure 6-5a) stimulates resistance to OA; CO_2-induced disturbances of growth and calcification were reversed by concomitant warming (Findlay et al., 2010; Sheppard-Brennand et al., 2010; Walther et al., 2011). Warming to above optimum temperatures, however, constrains performance and exacerbates sensitivity to hypoxia and/or elevated CO_2 (Figure 6-5, e.g., via decreased calcification; Rodolfo-Metalpa et al., 2011). Both hypoxia and/or elevated CO_2 in turn enhance heat sensitivity, as seen for CO_2 in crustaceans (via decreased heat limits: Walther et al., 2009; Findlay et al., 2010), coral reef fishes (via reduced performance: Munday et al., 2009b), and corals (via decreased calcification and CO_2-enhanced bleaching: Reynaud et al., 2003; Anthony et al., 2008). This translates into a narrowing of the thermal niche (Walther et al., 2009; see also Figure 6-5), which will shrink biogeographic ranges, affect species interactions, and shift phenologies (Figure 6-7a). Hence, extreme warming and hypoxia exacerbate CO_2 effects and vice versa (*medium confidence*). Such principles need to be reconfirmed across organism taxa (Pörtner, 2012).

Differences in organism adaptation to a climate zone's characteristic temperatures, temperature variability, oxygen content, and ocean chemistry may shape vulnerability to climate change. In high polar species evolutionary cold adaptation enhances vulnerability to warming

Table 6-4 | Potential interactions between modes of anthropogenic forcing (environmental; foodwebs; harvesting) on different levels of biological organisation. These interactions, from simple to complex, are illustrated with examples from the published literature. Unknown denotes no published information is available for each of these categories. NA denotes not applicable for this category.

Biological organization studied at ecosystem level	Anthropogenic forcing			
	Single environmental driver	Multiple environmental drivers	Fishing/foodwebs	Fishing/climate change
Individuals	Lab experiments and field observations show that warming alters organismal physiology and thereby growth (Pörtner and Knust, 2007).	Shipboard manipulation experiment addressing interactive effects of temperature and CO_2 on coccolithophore calcification (Feng et al., 2009).	NA	Unknown
Population	Physiological effects of warming change population abundance *in situ* (Pörtner and Knust, 2007). Lab cultures show how altered pH elicits different responses of coccolithophore species (Langer et al., 2006).	Lab cultures show differential responses of cyanobacterial groups to temperature and CO_2 (Fu et al., 2007).	Altered maturation age and growth rate of populations due to fishing (Fairweather et al., 2006; Hseih et al., 2006).	Interactive effects on cod populations of fishing and alteration of salinity (Lindegren et al., 2010).
Ecosystem	Mesocosm experiments simulating the effect of individual drivers (e.g., ocean acidification effects on benthos: Christen et al., 2013; and on pelagic communities: Riebesell et al., 2013).	Mesocosm experiments studying differential effects of light and temperature, on copepods versus diatoms (Lewandowska and Sommer, 2010).	Effects of fishing on ecosystem structure — trophic cascades (Frank et al., 2005).	Interplay of fishing and climate pressures on ecosystems promotes lower trophic levels (Kirby et al., 2009); enhances diversity loss in benthic communities (Griffith et al., 2011).
Biome	Time series observations on warming and geographical shifts of zooplankton biomes (Beaugrand et al., 2009).	Unknown	Unknown	Unknown

Approaches: = Experiments (lab or field) = Observations = Modeling = Not applied

(*medium confidence*). In OMZs, marine sediments, and in polar waters (due to high solubility in the cold), CO_2 levels are elevated and adaptation may reduce sensitivity and reliance on calcified structures (Clark et al., 2009; Walther et al., 2011; Maas et al., 2012). The observed shift from "overcalcified" to "weakly calcified" coccolithophores *Emiliania huxleyi* in cold waters may reflect a related shift in ecotype dominance (*limited evidence*, *medium agreement*; Cubillos et al., 2007).

Despite such potential adaptation, polar calcifiers exposed to higher CO_2 and lower carbonate saturation levels have been hypothesized to be highly sensitive to further CO_2 accumulation (*limited evidence*, *high agreement*; Orr et al., 2005). Here it appears relevant that cold temperature reduces energy demand and thereby lowers resistance to ocean acidification. Both energy demand and resistance are higher in eurytherms than in high polar and deep sea stenotherms (*limited evidence*, *medium agreement*; Pörtner, 2006; e.g., crustaceans: Pane and Barry, 2007: cf. Whiteley, 2011). In turn, tropical species may be more sensitive than temperate zone species (Pörtner et al., 2011). This rough differentiation of sensitivity is complicated by the local adaptation of populations from within-species genetic variability (*low confidence*).

Temperature influences hypoxia sensitivity (Section 6.3.3). Warming causes the minimum tolerated O_2 level to rise, enhancing vulnerability (*high confidence*). Conversely, hypoxia enhances vulnerability to warming in animals. This may occur fastest in warm oceans, where metabolic rates are higher and animals live closer to upper thermal limits (*medium confidence*; Pörtner, 2010). However, evolutionary adaptation has led to high hypoxia tolerance (low P_c or O_2crit values) in some warm-adapted coral reef fishes. Further warming then causes a rise in P_c which cannot be compensated for (Nilsson et al., 2010). Limits to hypoxia adaptation coincide with upper thermal limits (*medium confidence*).

Complexity in responses rises with the number of drivers involved. Enhanced river runoff and increased precipitation cause a shift from marine to more brackish and even freshwater communities, with unclear consequences for effects of other drivers. Falling primary production reduces resilience of higher trophic levels (Kirby and Beaugrand, 2009; Stock et al., 2011). The introduction of non-indigenous species, when supported by climate-induced shifts in interactions, may promote the displacement of ecotypes and shifts in ecosystem functioning, for example, in the Mediterranean Sea (Occhipinti-Ambrogi, 2007; Coll et al., 2010).

6.3.5.2. Microbes

Both synergistic and antagonistic effects of multiple drivers on microbial biota in the surface ocean have been observed in manipulation or modeling experiments (Folt et al., 1999; Boyd et al., 2010; Gruber, 2011). The productivity of many microbes was simultaneously limited by, for example, availability of nitrate and phosphate, cobalt and iron (Saito et al., 2002; Bertrand et al., 2007), or iron and light (Boyd et al., 2010; see also Section 6.2.2). Warming and high CO_2 synergistically enhanced photo-physiological rates of the cyanobacterium *Synechococcus*, whereas the cyanobacterial group *Prochlorococcus* showed no change (Fu et al., 2007). The magnitude of CO_2 effects on growth, fixation rates, or elemental ratios within single species is often strongly modulated by nutrient availability and light conditions (e.g., Sciandra et al., 2003; Zondervan et al., 2002; Kranz et al., 2010). Such differences cause floristic shifts in phytoplankton with the potential to restructure predator-prey interactions (Table 6-4).

Co-limiting factors vary by group, such as nitrogen fixers (e.g., Hutchins et al., 2007; Kranz et al., 2010), diatoms (Boyd et al., 2010), and coccolithophores (e.g., Feng et al., 2009; Rokitta and Rost, 2012). This limits the ability to project climate change effects (Boyd et al., 2010). The most reliable projections at ocean basin scale come from modeling, which mainly points to synergistic effects, such as those of elevated CO_2, hypoxia, and warming. For example, OA is projected to alter sinking particles (C:N ratio and/or reduced calcite content and slower sinking) with a consequent knock-on effect on water column O_2 demand already stimulated by warming, thereby causing expansion of OMZs (Gruber, 2011).

6.3.5.3. Animals and Plants

High oxygen availability alleviates thermal stress as seen in fish and mollusks (Mark et al., 2002; Pörtner et al., 2006). Conversely, hypoxia reduces heat tolerance (Section 6.3.5.1), but acclimation to hypoxia compensates for this and increases thermal tolerance (Burleson and Silva, 2011), for example, by enhancing blood pigment content or reducing energy demand. Tolerances to hypoxia and to high temperature may positively correlate in some fishes, indicating potential for adaptive evolution under climate change (*low confidence*; McBryan et al., 2013).

As a consequence of hypoxia narrowing thermal ranges (Section 6.3.5.1), combined warming and expanding hypoxia may cause mid-water mesopelagic and demersal fish stocks to decline at rates much quicker than anticipated in the California Current Ecosystem (McClatchie et al., 2010; Koslow et al., 2011). In benthic fauna, warming will also increase vulnerability to hypoxia. Experiments showed a rise in lethal oxygen concentrations by 25% and thereby reducing survival by 36% at 4°C warmer temperatures (Vaquer-Sunyer and Duarte, 2011). Hence, warming is expected to expand the area of ecosystems affected by hypoxia even if oxygen concentrations remain unchanged (*high confidence*). Under combined hypoxia and warming, CO_2 can extend short-term passive tolerance (despite constraining long-term tolerance). It facilitates a reduction in energy demand (Reipschläger et al., 1997; Pörtner et al., 2000), thereby extending survival of transient extremes of temperatures or hypoxia (*medium confidence*).

In macroalgae (non-calcifying) light availability modulates the response to elevated pCO_2 and temperature levels (Russell et al., 2011; Sarker et al., 2013). In warm-water corals, warming acting synergistically with CO_2 reduces calcification and increases sensitivity to bleaching (*high confidence*; Anthony et al., 2008). Combined warming and OA following SRES B1 (≈RCP4.5, reduced emission) and A1FI (≈RCP8.5, business-as-usual) scenarios in mesocosms caused losses of symbionts and corals, and a nocturnal decalcification of the reef community in summer. Present-day conditions already imply reduced resilience to episodic extreme events such as cyclones (Dove et al., 2013; see also Box CC-CR).

6.3.5.4. Ecosystems

The cumulative impacts of climate change drivers underlie alterations of species interactions and ecosystem structure and functioning, including changes in trophodynamics and the physical and chemical characteristics of habitats (*high confidence*). These effects combine with more indirect effects, such as shifts in stratification and productivity, expanding oxygen minimum zones, and the changing composition and biomass of food (partly resulting from direct effects on prey organisms) (*high confidence*). These complexities reduce the precision and reliability of quantitative projections (Section 6.5), including uncertainties concerning shifts in upwelling and their future role in global primary production and the development of fish stocks (Box CC-UP).

At the level of animal communities, effects of various drivers remain largely unexplored, some are highly complex. For example, the net eastward shift of Pacific skipjack tuna between 1980 and 2009 was linked to the shifting aggregation of macrozooplankton and micronekton, involving complex interactions of climate variability (due to ENSO; Section 30.5.2), warming ocean surface, shallowing mixed layer depth relative to the position of the warm pool, and the convergence of the pool with the Pacific Equatorial Divergence Province (Lehodey et al., 2011; see also Section 30.5.6.1.1). Interactive drivers will affect the relative performance of interacting species, thereby shifting species ranges, interactions, and food webs (*medium confidence*; Figure 6-7a). Adaptation to various climate zones modifies the roles of light and temperature in seasonalities and species interactions (Bradshaw and Holzapfel, 2010). Moderate hypoxia expansion in warming seas, for example, as the stratified central North Sea (Queste et al., 2013) may well influence the degree of temperature-induced species displacements (Figure 6-7b).

Impacts of climate change on benthic ecosystem engineers can also profoundly alter ecosystems. Tropical corals respond to ocean warming and acidification by increased bleaching, impeded calcification rates, and increased incidence of disease (*high confidence*; Veron et al., 2009; Veron, 2011; see also Sections 6.3.1-2, 30.5.6; Box CC-CR). In coral reefs under multiple stressors, differentiation of these large-scale phenomena into species-specific sensitivities is highly uncertain as trend data are virtually nonexistent (Brainard et al., 2011). Little is known about impacts on deep-water or cold-water corals and sponges, tropical calcified algae, bryozoans, sponges, and tube-forming serpulid worms (Wood, 1999). The reliance of all of these on surface productivity makes them vulnerable to any alteration in food supply. Projected severe stress from increased temperature, hypoxia, and ocean acidification will cause reduced performance and increasing mortality in ecosystem engineers (*high confidence*), and a deterioration of habitat characteristics for other organisms (*medium* to *low confidence*).

As a corollary, shifts in the geographical distributions of marine species (e.g., to higher latitudes or deeper waters; Figure 6-7b; Section 6.5.2) cause changes in community composition and interactions (Harley, 2011; Simpson et al., 2011; Hazen et al., 2013). Some species may gain predominance and abundance from fitness benefits (Figure 6-7) while others become less competitive or easier prey (Occhipinti-Ambrogi, 2007). Thereby, climate change will reassemble communities and affect biodiversity, with differences over time and between biomes and latitudes (*high confidence*; Parmesan and Matthews, 2005; Sala and Knowlton, 2006; Cheung et al., 2009; Parmesan et al., 2011; see also Box CC-PP; Section 6.5).

6.3.6. Food Web Consequences

Community reassembly under climate change involves a change in species composition and strongly alters food web structure, for example, causing shifts in trophic pathways (Kirby and Beaugrand, 2009; Moloney et al., 2011; see also Figure 6-12), some of which are irreversible (Jarre and Shannon, 2010). Through trophic cascades (Cury et al., 2003; Luczak et al., 2011), climate affects predation, competition, and food availability (e.g., via changes in NPP; Figure 6-12; Utne-Palm et al., 2010), including fish stocks (Parsons and Lear, 2001; Brown et al., 2010). Trophic amplification then drives an ecosystem towards a new stable structure or regime, which may be difficult to reverse (Folke et al., 2004). Warming may result in consumer control of food web structure because respiration of heterotrophic zooplankton and bacteria increases more strongly with warming than does photosynthesis of autotrophic phytoplankton (*medium confidence*; O'Connor et al., 2009).

Many impacts of climate change on food webs resemble those caused by fishing, pollution, eutrophication, and associated hypoxia (Section 6.3.3), and habitat change (Brander, 2007); unambiguous attribution to climate remains difficult (*low* to *medium confidence*; Parmesan et al., 2011). Some of these factors also affect food web responses to climate change. Fishing truncates the age and size structure of populations, making them more dependent on annual recruitment and reducing their ability to buffer environmental fluctuations (Genner et al., 2010; Planque et al., 2010; Botsford et al., 2011; see also Figure 6-12). Both adult and larval fishes show greater variability in abundance in exploited compared to unexploited populations (Hsieh et al., 2008). Warming, acidification, and removal of top or competing predators may all contribute to large fluctuations in gelatinous plankton (e.g., jellyfish) populations (*low confidence*; Molinero et al., 2005; Richardson and Gibbons, 2008; Richardson et al., 2009; Condon et al., 2012).

Analyzing impacts on key species provides insight into how individual components of a food web will respond to perturbations. However, projections of future states must include the complex food web interactions that influence the species and system-level responses, which affect stability and resilience of the overall ecosystem (Neutel et al., 2007; Dunne and Williams, 2009; Romanuk et al., 2009). There is no single approach currently available that includes the complex links within and among ecosystems, biogeochemistry, and climate as needed for projections of future states of marine food webs (Fulton, 2011; Moloney et al., 2011). In conclusion, there is *low confidence* in the quantitative projections of such changes (for further discussion see Section 6.5).

6.3.7. Marine Reptiles, Mammals, and Birds

6.3.7.1. Principles

Marine reptiles (turtles, snakes, crocodiles), mammals, and seabirds breathe air but live mostly in water; some shift or expand their ranges

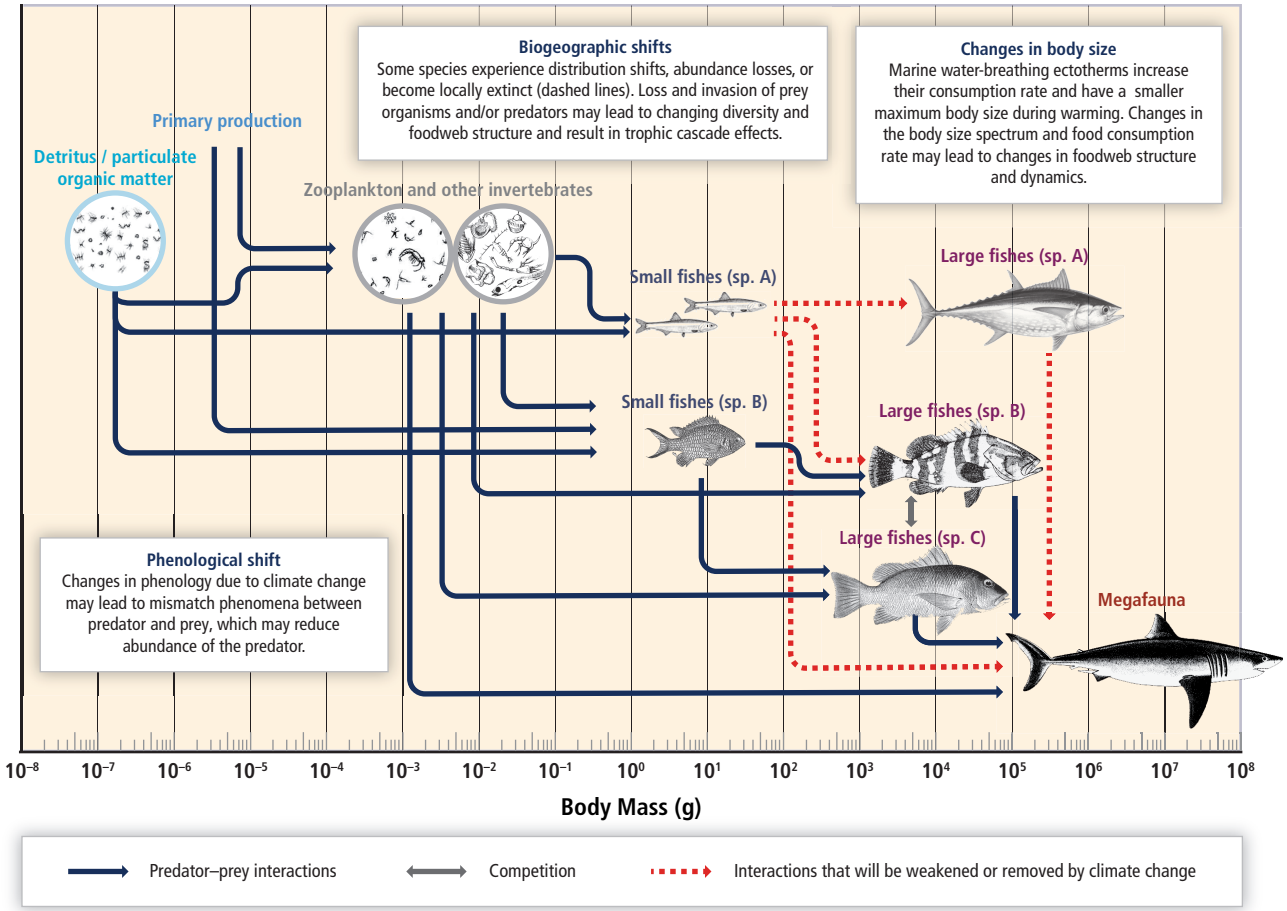


Figure 6-12 | Schematic diagram of expected responses to climate change in a marine food web. A coupled pelagic and benthic food web is structured by the body size spectrum of species. Combined warming, hypoxia, and ocean acidification reduce body size, shift biogeographies, change species composition and abundance, and reconfigure trophic linkages and interaction dynamics. Fishing generally removes large-bodied species and truncates the body-size spectrum of the community. This confounds the detection and attribution of food web responses to climate change. Arrows represent species interactions (e.g., between predator and prey or competitors for food or space). Broken lines reflect the potential loss of populations and trophic linkages due to climate change.

as a result of climate warming. The body temperature of ectothermic reptiles is set by ambient conditions; only at large body size may their body store heat and its temperature be higher than ambient. Reptiles are thus more responsive to temperature than homeothermic seabirds and marine mammals (McMahon and Hays, 2006), which regulate their body temperature by adjusting metabolic heat production and insulation from the environment, a trait beneficial especially in the cold. Various degrees of body core insulation in mammals and birds constrain their distribution to either warmer or colder waters (by poor or high insulation, respectively). However, large body sizes enable some aquatic air breathers to travel across the widest temperature ranges possible in some of the largest migrations on Earth.

Changes in water chemistry and hypoxia have minimal direct influences on the air-breathing vertebrates, reflecting their large independence from physical and chemical drivers in the oceans. There is evidence for increased sound propagation in a CO_2-enriched ocean, but no evidence yet for any effect on biota (Ilyina et al., 2010). If habitat structures offering retreat or ambush disappear, this will increase the energetic costs of life. Warming waters increase the cost of pursuit-diving as prey fishes increase swimming velocity. The predation success of such mammals (e.g., sea lions) and seabirds (e.g., penguins, cormorants) is thus constrained to waters ≤20°C (Cairns et al., 2008), a trend that extrapolates into the future (*low* to *medium confidence*). As prey distributions shift, foragers tied to land between trips may be constrained by the physiological costs of finding prey (Péron et al., 2012; Hazen et al., 2013). If food items are only found in thermally restricted areas or move to greater depths, mammals and birds may become constrained to certain distribution ranges or to the physiological limits of their diving ability (McIntyre et al., 2011). Conversely, hypoxic habitat compression for fishes may facilitate foraging opportunities for their air-breathing predators (Hazen et al., 2009). Accordingly, many air-breathers encounter changing habitat and food availability with climate change (*high confidence*).

6.3.7.2. Field Observations

Some species of seabirds, marine mammals, and sea turtles have responded to the anomalous ocean climate of the 20th century (*high confidence*; Hughes, 2000). There is insufficient information to assess effects on sea snakes or crocodiles. Poleward distribution shifts of turtles consistent with recent warming have been recorded in almost all marine groups. Decadal-scale climate fluctuations affect their recruitment

success and nesting abundance (Van Houtan and Halley, 2011), with an inverse correlation between warming and abundance in various species and regions (Balazs and Chaloupka, 2004; Chaloupka et al., 2008; Mazaris et al., 2009). Extreme weather causes nest flooding, considerably reducing hatching success (Van Houtan and Bass, 2007); projected sea level rise (WGI AR5 Chapter 13) will exacerbate such impact. Those with high fidelity to nesting and foraging sites (Cuevas et al., 2008) are impacted more than those capable of changing those sites (Fish et al., 2009; Hawkes et al., 2009). Continued warming, modulated by changing rainfall (Santidrián Tomillo et al., 2012), may skew turtle sex ratios toward females, increase egg and hatchling mortality (Fuentes et al., 2009), cause earlier onset of nesting (Pike et al., 2006; Mazaris et al., 2008), decrease nesting populations (Chaloupka et al., 2008), and shift dietary breadths (Hawkes et al., 2009), leading to projected recruitment declines (e.g., leatherback turtles; Saba et al., 2012). Vulnerability due to shifting sex ratio alone remains unclear, as nesting beaches have persisted with low production of male hatchlings over decades or longer (*low confidence*; Godfrey et al., 1999; Broderick et al., 2000; Hays et al., 2003). The absence of sea turtles in certain regions may be best explained by the temporal unavailability of food resources or strong thermoclines restricting their bottom foraging abilities (Braun-McNeill et al., 2008; Gardner et al., 2008).

Seabird range modifications probably caused by climate change were recorded in polar areas and the temperate zone of the North Atlantic (Grémillet and Boulinier, 2009). Temperate species have shifted their ranges to higher latitudes in both hemispheres (Bunce et al., 2002; Robinson et al., 2005; La Sorte and Jetz, 2010). Some species, like the king penguin, follow shifting foraging zones (Péron et al., 2012); others, such as the emperor penguin, are affected by changing habitat structure (sea ice; Jenouvrier et al., 2012). Warming causes many bird species to breed earlier (Sydeman and Bograd, 2009). High-latitude, cool-water species undergo extended breeding seasons (Chambers et al., 2011). There is often no agreement, whether changes reflect solely ocean warming, or a combination of factors, such as fishing pressure on seabirds' prey species, sea level rise, and pollution (Galbraith et al., 2005; Votier et al., 2005; Heath et al., 2009). Most shifts in range and seasonal activity involve shifts in trophic relationships (*medium confidence*). Seabirds with narrow geographic domains are expected to be more susceptible to climate change (Chambers et al., 2005; Grémillet and Boulinier, 2009), even leading to local extinctions (e.g., the Galápagos penguin: Vargas et al., 2007; or the marbled murrelet: Becker et al., 2007).

The distribution, phenology, and migratory timing of marine mammals are also shaped by predator-prey dynamics and climate impacts on specific habitats (Calambokidis et al., 2009; Salvadeo et al., 2011). Some marine mammals, that is, dolphin, porpoise, and whale species, shift their distribution poleward to follow the movement of their prey (*medium confidence*; Springer et al., 1999; MacLeod et al., 2005; Simmonds and Isaac, 2007; Salvadeo et al., 2010). As in birds, vulnerability to climate change is high for marine mammals with narrow geographic ranges and high habitat dependence. For example, the critically endangered vaquita, endemic to the Northern Gulf of California, cannot move north because of the land barrier (MacLeod, 2009). The polar bear (Laidre et al., 2008; Rode et al., 2012) and the walrus depend on sea ice as a platform for hunting, resting, and giving birth. For polar bears, access to prey such as ringed seals has been disrupted by the later formation and earlier breakup of sea ice in the eastern Canadian Arctic. Seasonal migrants into the Arctic (fin, minke, gray, killer, humpback whales) may increasingly compete with species adapted to operate in habitat with sea ice (some seals, narwhal, bowhead whale, beluga). Both may benefit from the net loss of sea ice, which will offer them better access to foraging in a pelagic-dominated ecosystem (Moore and Huntington, 2008).

6.3.8. Summary and Conclusions

An organism's capacity to perform, but also its access to food energy fueling that performance, shape its sensitivity to climate change (*high confidence*). Extreme temperatures surpassing the fringes of the thermal envelope cause local abundance losses, extinction, and shifts in temperature-dependent distribution ranges (*high confidence*; Section 6.3.1).

Some climate change effects detected in the field can be attributed to temperature, but few allow clear attribution to other drivers (Sections 6.3.1-5, 6.6). In fishes and invertebrates, specialization in regional climate regimes co-defines sensitivity to warming, acidification, and hypoxia (*high confidence*; Section 6.3.5). In marine mammals, birds, and ectothermic reptiles, changes in life history and population dynamics have often not been directly attributed to climate drivers (*low confidence*), but rather to the availability of habitat and food (*high confidence*; Section 6.3.7).

Natural climatic variability (Figure 6-1) and anthropogenic change, with a strong role of warming, cause large-scale changes in biogeography, abundance, diversity, community composition, and structure of marine species (*very high confidence*; Section 6.3.1). Warming reduces body size (*medium confidence*; Section 6.3.1). Differential species responses modify their interactions across trophic levels through trophic amplification (*medium* to *high confidence*; Section 6.3.6).

Some tropical species and ecosystems exist close to upper thermal limits placing them among the marine ecosystems most affected by climate change (*high confidence*; Section 6.3.1). Corals and coral reefs are primary examples. However, other factors change concomitantly, such that quantifying ecosystem changes attributable to warming or other drivers has not always been possible (Section 6.3.5).

Under future climate change ocean acidification will affect marine organisms and ecosystems for centuries (*high confidence*; Sections 6.3.2, 6.3.5). To date, very few ecosystem-level changes in the field have been attributed to anthropogenic or local ocean acidification (*medium confidence*; Section 6.3.2). Concomitant trends of warming, O_2 depletion, OA, and other drivers prevent clear attribution to OA (Section 6.3.5).

Elevated CO_2 levels stimulate primary production of some macroalgae and seagrass species (*high confidence*), causing them to be more competitive than calcifying organisms (*medium confidence*; Section 6.3.2). High sensitivities to OA are associated with low capacities to maintain pH in internal fluids (*high confidence*). Calcification rates in sensitive invertebrates, including corals, echinoderms, and mollusks, decrease under OA, especially if combined with temperature extremes

Frequently Asked Questions

FAQ 6.4 | What changes in marine ecosystems are likely because of climate change?

There is general consensus among scientists that climate change significantly affects marine ecosystems and may have profound impacts on future ocean biodiversity. Recent changes in the distribution of species as well as species richness within some marine communities and the structure of those communities have been attributed to ocean warming. Projected changes in physical and biogeochemical drivers such as temperature, CO_2 content and acidification, oxygen levels, the availability of nutrients, and the amount of ocean covered by ice will affect marine life.

Overall, climate change will lead to large-scale shifts in the patterns of marine productivity, biodiversity, community composition, and ecosystem structure. Regional extinction of species that are sensitive to climate change will lead to a decrease in species richness. In particular, the impacts of climate change on vulnerable organisms such as warm-water corals are expected to affect associated ecosystems, such as coral reef communities.

Ocean primary production of the phytoplankton at the base of the marine food chain is expected to change but the global patterns of these changes are difficult to project. Existing projections suggest an increase in primary production at high latitudes such as the Arctic and Southern Oceans (because the amount of sunlight available for photosynthesis of phytoplankton goes up as the amount of water covered by ice decreases). Decreases are projected for ocean primary production in the tropics and at mid-latitudes because of reduced nutrient supply. Alteration of the biology, distribution, and seasonal activity of marine organisms will disturb food web interactions such as the grazing of copepods (tiny crustaceans) on planktonic algae, another important foundational level of the marine food chain. Increasing temperature, nutrient fluctuations, and human-induced eutrophication may support the development of harmful algal blooms in coastal areas. Similar effects are expected in upwelling areas where wind and currents bring colder and nutrient-rich water to the surface. Climate change may also cause shifts in the distribution and abundance of pathogens such as those that cause cholera.

Most climate change scenarios foresee a shift or expansion of the ranges of many species of plankton, fish, and invertebrates toward higher latitudes, by tens of kilometers per decade, contributing to changes in species richness and altered community composition. Organisms less likely to shift to higher latitudes because they are more tolerant of the direct effects of climate change or less mobile may also be affected because climate change will alter the existing food webs on which they depend.

In polar areas, populations of species of invertebrates and fish adapted to colder waters may decline as they have no place to go. Some of those species may face local extinction. Some species in semi-enclosed seas such as the Wadden Sea and the Mediterranean Sea also face higher risk of local extinction because land boundaries around those bodies of water will make it difficult for those species to move laterally to escape waters that may be too warm.

(*high confidence*; Section 6.3.5). Thresholds beyond which effects occur can be quantified only with *low confidence*; there are differential sensitivities and thresholds between taxa and species (*high confidence*; Section 6.3.2).

Expansion of oxygen minimum zones leads to community shifts clearly attributable to extreme hypoxia (*high confidence*; Section 6.3.3). Gradual effects of a progressive decline in ocean O_2 levels on communities have not been sufficiently explored.

In general, community reassembly with new species coming in will occur in the transition to future climates (*medium confidence*) and lead to new ecosystem states (*low confidence*; Section 6.3.6). Climate change interacts with top-down human interferences, such as fisheries or other forms of harvesting, which accelerate impacts (*medium confidence*). Nonlinearities challenge the projection of marine ecosystem trajectories (FAQ 6.4).

In microbes, a conceptual foundation suitable to support an integrated understanding of climate impacts on individual species and communities is lacking. Specific physiological responses, such as in primary production, N_2 fixation, or calcification, can be attributed to multiple environmental drivers associated with climate change (*high confidence*; Sections 6.3.1-5).

6.4. Human Activities in Marine Ecosystems: Adaptation Benefits and Threats

Human societies benefit from resources and processes supplied by marine ecosystems, so-called ecosystem services. Attributing and projecting

ecosystem changes and their effects on human communities caused by climate change including ocean acidification is challenging. Insufficient observations compound an understanding of long-term changes and the definition of baseline conditions. Some of the challenges are related to the difficulty of projecting how human communities will adapt to changing marine ecosystem benefits.

6.4.1. Ecosystem Services

Marine ecosystem services (e.g., Chapter 5) include products (food, fuel, biochemical resources), climate regulation and biogeochemical processes (CO_2 uptake, carbon storage, microbial water purification), coastal protection, provision of space and waterways for maritime transport, cultural services (recreational and spiritual opportunities, aesthetic enjoyment), and functions supporting all other ecosystem services (nutrient cycling, photosynthesis, habitat creation). Most components of the marine environment contribute to more than one major category of ecosystem service: for example, ocean primary productivity is classified as a supporting service, but it affects provisioning services via changes in fisheries, generation of fossil fuel resources, regulating services via the global carbon cycle and climate regulation, and cultural services via the enjoyment of a healthy ecosystem. Rarely has economic damage of climate change to a whole ecosystem been evaluated and projected. The projected loss of tropical reef cover due to ocean acidification under SRES A1 and B2 scenarios will cause damages of US$870 and 528 billion (year 2000 value) by 2100, respectively (cost rising with parallel economic growth; Brander et al., 2012; see also Box CC-OA). Such loss is felt most strongly in the respective regions.

6.4.1.1. Food from the Sea

Fisheries provide 3 billion people with almost 20% of their average per capita intake of animal protein (FAO, 2012a), 400 million depend critically on fish for their food (Garcia and Rosenberg, 2010). Total world marine capture fisheries catches stabilized in the mid-1990s at about 90 million tons per year. Marine aquaculture of primarily mollusks and crustaceans contributes more than 63 million tons annually to seafood production, mostly concentrated in coastal areas (FAO, 2012b). The growth of aquaculture has decelerated, but is still considered a development opportunity and a strong need in regions such as Africa and Latin America (Section 7.4.2.2).

Climate-induced shifts in ecosystems and fisheries production will create significant challenges to sustainability and management (Section 7.5.1.1.3), particularly for countries with fewer resources and lower adaptive capacity, including many low-latitude and small island nations (*high confidence*; Allison et al., 2009; Worm et al., 2009; Cooley et al., 2012; see also Sections 7.2.1.2, 7.4.2.1, 30.6.2; WGIII AR5 Section 2.1). Vulnerability will be exacerbated by increases in the frequency and severity of extreme events (e.g., floods or storms) damaging infrastructure, homes, health, livelihoods, or non-marine food security (Kovats et al., 2003; Rosegrant and Cline, 2003; Adger et al., 2005; Haines et al., 2006).

The projected trends in fish stocks will widen the disparity in food security between developing and developed nations. Fish migrations due to warming (Section 6.3.1) have already shifted the composition of fisheries catches (Pinsky and Fogarty, 2012; Cheung et al., 2013a) and altered stock distributions (Sabatés et al., 2006). Further warming may be beneficial for fisheries productivity in some regions such as the North Atlantic, because of the poleward shift of exploited species and changes in primary productivity (Arnason, 2007; Stenevik and Sundby, 2007; Cheung et al., 2010; see also Box 6-1; Section 30.5.1.1.1), or for some Pacific Islands due to the eastward redistribution of tuna stocks (Lehodey, 2000; Lehodey et al., 2011). Resulting changes in accessibility and fishing operations costs are projected to straddle economic zones, perturb international fishery agreements, and cause excessive exploitation (Hannesson, 2007; Sumaila et al., 2011; see also Sections 7.3.2.4, 7.4.2; WGIII AR5 Section 4.3.7).

Invertebrate fisheries and aquaculture appear very vulnerable to the impacts of ocean acidification (Barton et al., 2012; see also Box CC-OA; Figure 6-10). This concerns especially shelled mollusks, with a substantial decline in their global production projected between 2020 and 2060 under the SRES A2 business-as-usual scenario (Cooley and Doney, 2009; Cooley et al., 2012). Effects on calcifying plankton will propagate through the food web, making estimates of economic impact on fish catch by OA difficult, also due to complex interactions with other stressors like warming and fisheries management (Griffith et al., 2012; Branch et al., 2013). Model projections suggest a potential loss of up to 13% (SRES A1FI scenario) to annual total fishery value in the USA, or globally more than US$100 billion annually by 2100 (Cooley and Doney, 2009; Narita et al., 2012). Vulnerability differs highly between nations according to the contribution of such fisheries to their economy (Cooley et al., 2012; see also Sections 7.3.2.4, 7.4.2). These projections are sensitive to the projected vulnerabilities of the organisms to ocean acidification (*medium confidence*; Section 6.3.2).

Fishing reduces abundances at high trophic levels, but increases abundances at mid-trophic levels. It reduces species numbers, simplifies ecosystem structure, and increases ecosystem sensitivity to climate change (Perry et al., 2010). Exploitation of fish stocks and the alteration of their demography, population dynamics, and life history traits (Petitgas et al., 2006; Perry et al., 2010; Planque et al., 2010) can reduce the capacity of fish populations to buffer changes in climate variability (Ottersen et al., 2006; Genner et al., 2010), and increase variability in population size. Interactions between warming, OA, and human activities such as fishing may thus exacerbate climate impacts on a wide range of ocean processes and services, including marine fisheries (*medium confidence*; Tables 6-4, 6-6; Section 30.6.2).

A 2°C global temperature increase by 2050 is estimated to cause global losses in landed value of US$17 to 41 billion annually (in 2005 value), with an estimated cost of adaptation for the fisheries of US$7 to 30 billion annually over a 40-year time frame between 2010 and 2050. The largest loss in landed value is projected to occur in East Asia and the Pacific (*low confidence*; Sumaila and Cheung, 2010). Overall impacts and the regional manifestations will partially depend on the flexibility and response capacities of food production systems (Elmqvist et al., 2003; Planque et al., 2011a).

Specific implications for the fishing industry are still poorly known, as future projections of shifts in primary production and knock-on effects

through food webs and into fisheries remain uncertain (*low confidence* in effects of changing NPP; Planque et al., 2011b; Stock et al., 2011).

6.4.1.2. Other Provisioning Services

Reductions in marine biodiversity due to climate change and other anthropogenic stressors (Tittensor et al., 2010), such as OA (CBD, 2009) and pollution, might reduce the discovery of genetic resources from marine species useful in pharmaceutical, aquaculture, agriculture, and other industries (Arrieta et al., 2010), leading to a loss of option value from marine ecosystems. Climate change increases the demand for marine renewable energy such as wind and wave power, though with potential ecosystem impacts of their infrastructure (Section 6.4.2).

6.4.1.3. Climate Regulation and Extreme Events

The effect of climate change on marine biota will alter their contribution to climate regulation, that is, the maintenance of the chemical composition and physical processes in the atmosphere and oceans (*high confidence*; Beaumont et al., 2007). Regulatory mechanisms in which organisms (especially phytoplankton) play a key role, include control of the level of atmospheric CO_2 through the balance between photosynthesis and respiration (Johnson et al., 2010), and through the biological and alkalinity pump (Falkowski, 1997; Feely et al., 2008). They also include the modulation of further greenhouse gases such as nitrous oxide (N_2O; Jin and Gruber, 2003; Law, 2008; see also Section 6.1.1.3), and the modulation of other climatically reactive gases such as dimethylsulfide (DMS; Vogt et al., 2008). A projected decrease in global ocean NPP (Section 6.5.1) may result in decreased export of biogenic carbon to the deep ocean (Bopp et al., 2002; Boyd and Doney, 2002; Hashioka and Yamanaka, 2007). A positive feedback on climate change may result; however, many of the factors controlling the pump are poorly understood (Figure 6-4; WGI AR5 Chapter 6).

Coastal marine ecosystems reduce the effects of floods and storm surges which account for most of the natural disasters affecting people in coastal regions (IPCC, 2012a). Empirical and modeling studies show that coral reefs contribute to buffering the impact of tsunamis (Fernando et al., 2005; Gravelle and Mimura, 2008; see also Sections 5.4.2.4, 30.5; Box CC-CR). Experiments and models indicate that warming and OA slow coral growth by nearly 50% by 2050 (Box CC-CR; Section 5.4.2.4), making some islands and coastal areas more vulnerable to tsunamis, storm surges, wave energy, and coastal erosion (*high confidence*). Wetlands and mangroves provide biologically diverse buffer zones (Section 5.4.2.3). The combined impacts of climate change, pollution, deoxygenation, and other overlapping stressors, on mangroves and wetlands have not been determined (Cooley et al., 2009; Cooley, 2012). Some of these stressors enhance each other's effects in coastal systems (Feely et al., 2010; Cai et al., 2011; Howarth et al., 2011).

6.4.1.4. Cultural Services

Cultural services encompass a wide array of services with marine biodiversity as a core component supporting recreation and tourism as the economically most relevant. Tropical coral reefs and their enormous biodiversity sustain substantial tourist industries, presently with global annual net benefits of about US$9.6 billion (Cesar et al., 2003; see also Box CC-CR; Section 30.6.2.2). If reef services degrade, coastal visitors might choose alternative attractions (UNWTO, 2008). Increased travel to see disappearing ecosystem types (e.g., Antarctica: Liggett et al., 2011) or in previously inhospitable areas or seasons (Amelung et al., 2007; Moore, 2010) create new pressures and are unsustainable as the locations of key attractors shift (e.g., cetaceans: Lambert et al., 2010; Salvadeo et al., 2013).

Climate change may endanger harvests of marine species with spiritual and aesthetic importance to indigenous cultures, raising ethical questions about cultural preservation (e.g., Nuttall, 1998). In coastal communities, losing the aesthetic values of marine ecosystems may harm local economies: better water quality and fewer harmful algal blooms are related to higher shellfish landings and real estate prices (Jin et al., 2008).

Some heritage benefits of preserving marine ecosystems consist of the economic value of a healthy, diverse ecosystem to future generations. Any climate-related biodiversity loss or pollution of marine ecosystems would decrease the bank of resources for future opportunities. For example, the research and conservation value of coral reef biodiversity and its non-use value are estimated together at US$5.5 billion annually (Cesar et al., 2003). As with spiritual and aesthetic benefits, maintaining heritage benefits under climate change poses challenges for managers concerning equity and ethics as well as multigenerational (and possibly multi-cultural) ethical questions.

6.4.1.5. Supporting Services

Fully identifying the services supporting other ecosystem benefits is virtually impossible, as they are diverse in nature and scale. Ecosystem engineers play an important role in these services. Damage to calcifying algae and corals will reduce habitat for other species (Section 6.3.5), biodiversity, cultural and leisure values, and their climate regulation capacity.

Waterways for shipping are expected to change in the next several decades (*very high confidence*; Chapter 28; Section 30.6.2.3). Reductions in Arctic sea ice allow new trade routes such as the Northwest Passage (Wilson et al., 2004; Granier et al., 2006), enabling economically viable trans-Arctic shipping, and access to regional resources for exploitation and tourism. This development would increase emission of greenhouse gases and other pollutants (Lauer et al., 2009; Corbett et al., 2010), and facilitate the invasion of non-indigenous species carried on hulls and in ballast waters (Lewis et al., 2004).

6.4.2. Management-Related Adaptations and Risks

6.4.2.1. Ecosystem Management

A changing climate will have both positive and negative consequences for managing ocean resources (*high confidence*) (Eide and Heen, 2002;

Eide, 2007; see also Section 6.4.1). Ecosystem-based management (EBM, an approach recognizing all, including human interactions, within an ecosystem) or the ecosystem approach (EA, a strategy for the integrated management of living resources promoting both conservation and sustainable use) are increasingly adopted globally (FAO, 2003) to deal with the multitude of human pressures on marine ecosystems (Sherman et al., 2005; Hoel, 2009). Extended EBM addresses changes driven by climate and human activities, considering that diverse drivers will interact and confound each other (Planque et al., 2010; Eero et al., 2011; see also Section 6.3.5). Human activities will undermine resilience to other, including climate, impacts or undermine the effectiveness of mitigation and adaptation measures, by increasing variability (thereby reducing predictability), and limiting scope for adaptation (*high confidence*; e.g., Hughes, 2004; Sissener and Bjørndal, 2005; Eero et al., 2011). Thus, managing ecosystems under climate change increases the resilience of ecosystems and adaptive capacity of management systems through reducing other human perturbations (e.g., overfishing) (Brander, 2008; see also Section 7.5.1.1.3). Managing ecosystems also reduces the consequences of ocean acidification until CO_2 emission reduction becomes effective (Rau et al., 2012; Billé et al., 2013; McLeod et al., 2013; see also Box CC-OA). Ecosystem resilience is enhanced by reducing regional eutrophication (Falkenberg et al., 2013), or in aquaculture by avoiding acidified water (Barton et al., 2012) and by selecting and cultivating pre-adapted strains (Parker et al., 2012).

However, effects of climate change cannot be reversed by reducing the impacts of non-climatic drivers, emphasizing the need for adaptive management. Increased variability of ecosystem responses to climate change and the low predictability of some biological responses undermine the effectiveness of management and conservation measures. A particular risk is that climate change may contribute to large-scale ecosystem regime shifts (Section 6.3.1.5; Box 6-1). Detecting and forecasting such shifts from time series of environmental and biological data (Carpenter and Brock, 2006; deYoung et al., 2008), is constrained by an insufficient number of observations and limited quantitative understanding (Section 6.1.2). Biogeographic shifts challenge spatial management (Box CC-MB; Sections 6.3.1, 6.5), which is a fundamental part of EBM (Douvere, 2008), and demand that "fixed in law forever" site-attached zoning to protect specific species may need to become more flexible to maintain the original objectives as species move or community structures shift (*high confidence*; Soto, 2001; Hawkins, 2012).

6.4.2.2. Geoengineering Approaches

Geoengineering approaches to mitigate climate change and its effects, include Solar Radiation Management (SRM) and Carbon Dioxide Removal (CDR; see Table 6-5; IPCC, 2012b). SRM aims to reduce warming by increasing albedo, for example, via stratospheric injection of sulfate aerosol (Crutzen, 2006). SRM may affect marine ecosystems through changes in precipitation. With continued CO_2 emissions it leaves ocean acidification largely unabated as it cannot mitigate rising atmospheric CO_2 concentrations (Vaughan and Lenton, 2011; Williamson and Turley, 2012). Termination of SRM after its implementation involves the risk of rapid climate change and more severe effects on ecosystems (Russell et al., 2012).

Proposed CDR techniques include both ocean- and land-based approaches (Vaughan and Lenton, 2011; see also Section 30.6.4). CO_2 storage in geological reservoirs may occur beneath the seafloor, for example, in porous marine aquifers, and includes the risk of CO_2 leakage to the marine environment. Proposals to directly or indirectly sequester CO_2 into the ocean (Caldeira et al., 2005; Boyd, 2008; Shepherd et al., 2009; see also Table 6-5; WGIII AR5 Section 7.5.5) include, among others, the use of ocean fertilization techniques by nutrient addition, the direct storage of biomass in the deep ocean, the addition of alkalinity for build-up of dissolved inorganic carbon (DIC; i.e., carbonate), and the direct CO_2 injection into the deep ocean (Williamson et al., 2012). All of these approaches have potentially negative consequences for marine ecosystems.

Ocean fertilization by adding iron to high-nutrient low-chlorophyll (HNLC) oceanic waters could increase productivity and the net export of organic material to the deep ocean and its consecutive decomposition, causing deep-water accumulation of CO_2. Fertilization would affect all major marine biogeochemical cycles of the ocean with unclear side effects that could include the formation of methane (CH_4) and N_2O (Law, 2008) or the stimulation of harmful algal blooms (Trick et al., 2010). The enhanced NPP would add more carbon to the base of food webs (de Baar et al., 2005) and stimulate growth, for example, of deep-sea benthos (Wolff et al., 2011). Any regional increase in organic material (through fertilization or intentional storage of biomass) would cause enhanced O_2 demand and deep-water O_2 depletion (Sarmiento et al., 2010; Table 6-5), increasing the level and extent of hypoxia and associated impacts on marine ecosystems (Sections 6.3.3, 6.3.5, 30.5.7). The synergistic effects of CO_2-induced acidification will exacerbate the biological impacts (*high confidence*).

Neutralizing the acidifying water by the addition of alkalinity, for example, calcium oxide, would require large-scale terrestrial mining with associated consequences (Caldeira et al., 2005). The biological effects of increased concentrations of Ca^{2+} ions and dissolved inorganic carbon remain insufficiently explored. Direct injection of CO_2 or its localized disposal in the ocean (e.g., as a lake in a deep-sea valley) causes locally highly increased CO_2 and acidification effects on deep-sea organisms (*high confidence*; Caldeira et al., 2005; see also Section 6.3.3.4). In contrast to long-term ocean fertilization or storage of biomass, this technique leaves the oxygen inventory of the deep ocean untouched (*limited evidence*, *medium agreement*; Pörtner et al., 2005).

The knowledge base on the implementation of SRM and CDR techniques and associated risks is presently insufficient. Comparative assessments suggest that the main ocean-related geoengineering approaches are very costly and have large environmental footprints (*high confidence*; Boyd, 2008; Vaughan and Lenton, 2011; Russell et al., 2012).

6.4.2.3. Health Issues

Human health and near-shore ecosystems may be directly impacted by climate change effects on harmful algal blooms (HABs; Edwards et al., 2006; see also Section 30.6.3) or disease vectors. Planktonic time-series archives and nearshore sediment cores containing HAB cysts have revealed few examples of strong linkages between altered HABs and

Table 6-5 | Challenges for the oceans that will arise from the employment of a range of geoengineering methods (SRM = solar radiation management; CDR = carbon dioxide removal).

Topic	Brief description	Challenge and impact	References
Solar radiation management techniques	Deflection of approximately 1.8% of sunlight, by various techniques, is able to offset the global mean temperature effects of a doubling of atmospheric CO_2 content from pre-industrial values.	Will leave ocean acidification unabated (*high confidence*). Response of primary production to light reduction unclear.	Crutzen (2006); Caldeira and Wood (2008)
Ocean storage by direct injection	Capture of CO_2 post-combustion from mainly coastal power plants, followed by injection of liquid CO_2 by pipeline or from a ship into the deep ocean.	Will add to ocean acidification and create localized harm to marine life (*high confidence*). Quantities will be small relative to the atmospheric invasion signal. CO_2 injected will dissolve and be transported by ocean circulation with eventual surface exposure.	Caldeira et al. (2005)
Sub-sea geologic storage	Capture of CO_2 from extracted gas or from post-combustion followed by well injection into a porous submarine aquifer beneath impermeable geologic strata.	Extensive experience in place from the Norwegian Sleipner field activity in the North Sea. No evidence of ocean impact from leakage to date.	Benson et al. (2005)
Ocean fertilization	Spreading of trace amounts of reduced iron over very large areas of the surface ocean where excess nutrients occur. Overcoming the local iron deficiency creates extensive phytoplankton blooms drawing down sea surface pCO_2. Fertilization can also be carried out by using direct or indirect (ocean pipes) addition of macronutrients to oceanic regions where they are depleted.	Much of the exported organic matter is remineralized at shallow depths, creating local oxygen stress and shallow CO_2 enrichment and methane and N_2O production. These effects are temporary and the effective retention time is short. If sustained, reduced surface ocean and increased deep ocean acidification. O_2 loss in ocean interior (*medium confidence*).	de Baar et al. (1995); de Baar et al. (2005); Pörtner et al. (2005); Boyd et al. (2007); Buesseler et al. (2008); Law (2008); Cao and Caldeira (2010)
Artificial upwelling or downwelling	Ocean fertilization by bringing nutrient rich deep water (from 200 to 1000 m) to the surface. Downwelling occurs in parallel, transporting physically dissolved CO_2 into the deep ocean.	Deep water contains high levels of CO_2, which if released counteracts the binding of CO_2 by fertilization. No evidence available.	Lovelock and Rapley (2007); Oschlies et al. (2010)
Sequestration of organic carbon	Storage of terrestrial biomass in the coastal or deep ocean.	Physical impact, regional loss of oxygen, CO_2 accumulation and acidification during degradation; increases in methane, N_2O, and H_2S. No evidence available.	Metzger and Benford (2001); Strand and Benford (2009)
Carbonate neutralization	Dissolution of power plant flue gas into sea water yielding an acidic solution that is neutralized by addition of crushed limestone. The resulting bicarbonate-rich fluid is discharged to the ocean.	Involves the transport and crushing to fine scale of large quantities of limestone and the processing of very large quantities of sea water. Environmental impact issues not yet explored.	Rau (2011)
Accelerated olivine weathering	Uses wind powered electrochemical processes to remove HCl from the ocean and neutralizes the acid with silicate minerals such as olivine for disposal. The net result is to add alkalinity to the ocean akin to natural silicate weathering processes.	Complex system as yet untested in pilot processes. Involves mining and crushing large quantities of silicate minerals. Very long time scale consequences uncertain.	House et al. (2007); Köhler et al. (2010)

climate fluctuations (Dale et al., 2006; see also Section 30.5.3.1.2). HABs can be stimulated by warming, nutrient fluctuations in upwelling areas, eutrophication in coastal areas, and enhanced surface stratification (*medium confidence*). Species-specific responses involve shifts in seasonal cycles and blooms (Johns et al., 2003). Ocean acidification may exacerbate the toxicity of species in coastal oceans under nutrient-limited conditions (Tatters et al., 2012; Sun et al., 2011). Suitable adaptation measures include appropriate monitoring of biotoxin problems (Hallegraeff, 2010).

Continued warming of tropical and temperate coastal habitats, excessive nutrient loading leading to phytoplankton and zooplankton blooms, and sea water inundation due to sea level rise are all projected to exacerbate the expansion and threat of cholera (*medium confidence*; see also Sections 11.5.2.1, 30.6.3), although attribution to climate change is confounded by climate variability and non-climate drivers (Lafferty, 2009; Dobson, 2009).

Cholera and its pathogen, the marine bacterium, *Vibrio cholera*, have been widely studied. The pathogen associates with marine organisms, especially chitinized zooplankton (Vezzulli et al., 2010). Where cholera is endemic (e.g., India, Bangladesh, Latin America), outbreaks correlate with warming and high zooplankton abundance (Lobitz et al., 2000; Lipp et al., 2002). Based on an 18-year climate record for Bangladesh, Pascual et al. (2000) reported cholera outbreaks at ENSO events, and the recent reappearance of cholera in Peru has also been linked to the intense 1991–1992 ENSO (Lipp et al., 2002). An increase in sustained maximum temperatures of the Baltic Sea (Section 30.5.3.1.4) has been related to an increase in reported *Vibrio* infections; highest human mortality rates were associated with *V. vulnificus* infections (Baker-Austin et al., 2013). Continued warming of tropical and temperate coastal habitats, excessive nutrient loading leading to phytoplankton and zooplankton blooms, and seawater inundation due to sea level rise are all projected to exacerbate the expansion and threat of cholera (*medium confidence*).

Ciguatera poisoning may occur when people consume fish, mainly from tropical reefs, that have ciguatoxins from the epiphytic dinoflagellate *Gambierdiscus* sp. Historical records show significant correlations between ciguatera poisoning and sea surface temperature in South Pacific nations (Hales et al., 1999). However, the relationship is nonlinear and dependent on the thermal window of the specific dinoflagellate (Llewellyn, 2010). This casts doubt on the accuracy of projected increases in ciguatera poisoning using linear extrapolations from observations (*low confidence*).

6.4.3. Conclusions

Human societies benefit from and depend on marine ecosystem services, including the provisioning of food and other goods, regulation of climate and extreme events, and cultural and supporting services (Section 6.4.1). Attributing and projecting climate-change-mediated shifts in these services remains a challenge, due to the intrinsic difficulty of assessments, lack of baseline and long time series data, and confounding human impacts. However, empirical and modeling studies indicate that climate change impacts on marine ecosystems lead to changes in provisioning, regulating, and supporting services (*high confidence*), as well as cultural services (*limited evidence*, *medium agreement*).

Food production from the sea is facing diverse stressors (Section 6.4.1.1), such as overfishing and habitat degradation, which interact with climate change phenomena, including warming (Section 6.3.1), ocean acidification (Section 6.3.2), and hypoxia (Section 6.3.3). Projections of impacts on capture fisheries are constrained by uncertainties in marine primary production (*medium evidence*, *medium agreement*; Section 6.5.1). Negative effects are projected to be most significant in developing nations in tropical regions (*high confidence*). Nations at higher latitudes may even benefit from climate change effects on ocean ecosystems, at least initially (Section 6.5.3).

Climate change effects on biota will alter their climate regulation through mechanisms such as carbonate production, the biological pump, the balance between photosynthesis and respiration, and the modulation of greenhouse gases (*high confidence*; Section 6.4.1.3). However, projections of the direction and magnitudes of feedbacks are at an early stage (*low confidence*).

Future management of ecosystems and fisheries might have to aim for increasing ecosystem resilience to climate change, for example, through reductions of other human perturbations (Section 6.4.2.1). Active ocean geoengineering strategies to ameliorate climate change may prove detrimental to the functioning of ecosystems, which highlights the need for further research and careful governance (Section 6.4.2.2). There is limited understanding of how harmful algal blooms and pathogens affecting human health will respond to climate change (Section 6.4.2.3; *medium* to *low confidence*).

6.5. Projections of Future Climate Change Impacts through Modeling Approaches

A range of models explore climate change effects on marine biota, from primary producers to higher trophic levels, and test hypotheses about responses of marine species, food webs, and ecosystems (Rose et al., 2010; Fulton et al., 2011; Stock et al., 2011; see also FAQ 6.2). Both empirical and mechanistic approaches are used over a range of temporal and spatial scales (Barange et al., 2010; Stock et al., 2011). There is an increasing need for upscaling from molecular and physiological to ecosystem level (e.g., Le Quesne and Pinnegar, 2012). Uncertainty in projections of changes in marine ecosystems is partly contingent on the level of confidence in climatic and oceanographic projections (Section 6.1.1; WGI AR5 Section 9.8). Models are currently useful for developing scenarios of directional changes in net primary productivity, species distributions, community structure, and trophic dynamics of marine ecosystems, as well as their implications for ecosystem goods and services under climate change. However, specific quantitative projections by these models remain imprecise (*low confidence*; Hannah et al., 2010; Rose et al., 2010; Stock et al., 2011; FAQ 6.4).

Earth System Models couple atmosphere, cryosphere, and hydrosphere (including the oceans), as well as climate and carbon cycles, and project changes in ocean biogeochemistry under a range of CO_2 emission scenarios (WGI AR5 Chapter 6). Models focusing on population and species level responses comprise models of population dynamics, models of species distribution, and models which explicitly link effects of changes in ocean physics and chemistry to changes in interactions between species at different trophic levels, or human activities such as fishing and aquaculture (Rose et al., 2010).

6.5.1. Oceanic Primary Production

Climate-induced effects on global ocean NPP comprise changes in its long-term average, seasonal timing, and peak amplitude (Henson et al., 2013). The magnitude, direction, and pattern of projected changes vary with differences in model structure and parameterization (Box CC-PP; Figure 6-13). Unknown accuracy of current NPP observations further increases the uncertainty of projections, as does the incomplete understanding of effects of multiple drivers on NPP (Sections 6.3.1-5, 6.4). Global coupled climate-ocean biogeochemical Earth System Models (WGI AR5 Chapter 6) project an increase in NPP at high latitudes but a decrease in permanently stratified oceans at mid-latitudes, in the tropics (west tropical Pacific, tropical Indian Ocean, tropical Atlantic), and in the North Atlantic (*medium confidence*; Steinacher et al., 2010; Bopp et al., 2013) (Figure 6-13). The overall result is a reduction in global mean NPP under all RCP scenarios (*medium confidence* in the direction of projected trends, *low confidence* in the magnitude of change).

6.5.2. Higher Trophic Levels

Projected future changes in temperature and other physical and chemical oceanographic factors are expected to affect the distribution and abundance of marine fishes and invertebrates, as elaborated by species distribution models. Limits of distribution ranges of 1066 exploited species are projected to undergo shifts by a median of around 50 km per decade to higher latitudes by 2050 relative to 2000 under the SRES A1B (≈RCP6.0) scenario (Cheung et al., 2009). Some species shift toward the equator following a regional temperature gradient (Burrows et al., 2011; Cheung et al., 2013b; Pinsky et al., 2013). The rate of range shifts is projected to be three times higher for pelagic than for demersal fishes (Cheung et al., 2009), the latter shifting at a rate of around 27 to 36 km per decade (Cheung et al., 2013b). However, the expansion of hypoxic waters may have a greater impact than warming on demersal fishes (Koslow et al., 2011). As a result of distribution shifts, high-latitude regions (the Arctic, Southern Ocean) are projected to have high rates of species invasions. Intermediate latitudes are expected to undergo both invasions and local extinctions. High rates of local extinction are projected for the tropics and semi-enclosed seas (e.g., Mediterranean Sea, Persian Gulf). In addition, the future productivity and distribution

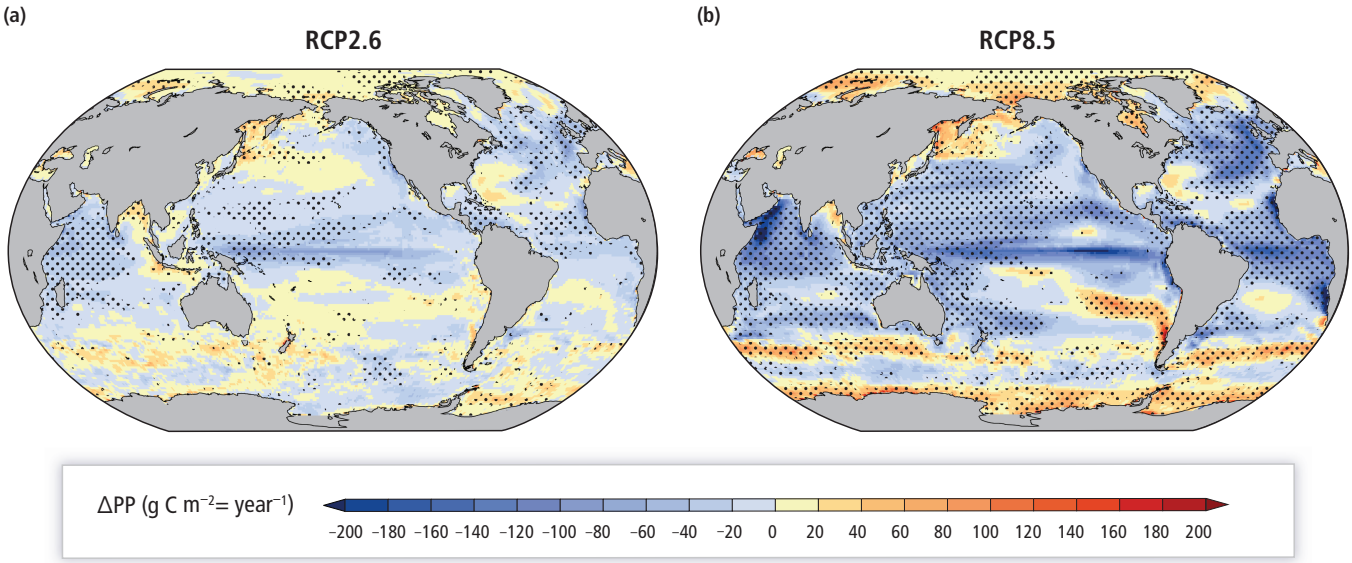


Figure 6-13 | Multi-model annual mean changes of projected vertically integrated net primary production (small and large phytoplankton) under the low-emission scenario Representative Concentration Pathway 2.6 (RCP2.6) (a) and the high-emission scenario RCP8.5 (b) for the period 2090 to 2099 relative to 1990 to 1999 (after Bopp et al., 2013). To indicate consistency in the sign of change, regions are stippled where 80% of the 10 models from the Coupled Model Intercomparison Project Phase 5 (Bopp et al. 2013) agree on the sign of change.

of higher trophic level organisms are projected to change due to changes in primary productivity (Section 6.3.6). For example, the migration route of Pacific sardine is projected to shift because of changes in primary productivity and food availability (Ito et al., 2010). The global pattern of distribution shifts is generally consistent with regional-scale projections and past observations (e.g., Lenoir et al., 2011; Cheung et al., 2013a). However, detailed quantitative projections are sensitive to model structure and assumptions (Hare et al., 2012; Jones et al., 2013) and responses of specific populations may differ from average species responses (Hazen et al., 2013).

Coral reefs are projected to undergo long-term degradation by 2020 to 2100 relative to the 2000s under RCP2.6, 4.5, and 8.5 or their equivalents (Section 30.5.6). Reefs projected to be threatened most by bleaching under the SRES A1B scenario by 2100 include the Central and Western Equatorial Pacific, Coral Triangle, and parts of Micronesia and Melanesia (Teneva et al., 2012). These projections assume that coral bleaching occurs when SST exceeds a certain threshold, and that there is limited potential to shift such threshold by adaptation. Reef degradation will impact ecosystem services (Hoegh-Guldberg, 2011; see also Section 6.4; Box CC-CR).

Some groups of marine air-breathing fauna are projected to shift in distribution and abundance (Section 6.3.7). Cetacean richness will increase above 40° latitude in both hemispheres, while at lower latitudes both pinniped and cetacean richness are projected to decrease by 2040–2049 relative to 1990–1999 under the SRES A1B scenario (Kaschner et al., 2011). Using SST as a predictor, the distribution of loggerhead turtles is projected to expand poleward in the Atlantic Ocean and to gain habitat in the Mediterranean Sea by 2070–2089 relative to 1970–1989 (Witt et al., 2010). Leatherback turtle may decrease in abundance at a rate of 7% per decade because of reduced hatching success with warming following the SRES A2 scenario (Saba et al., 2012). Abundances of some seabirds such as European breeding seabirds (Huntley et al., 2007), Cassin's auklet in the California Current Ecosystem, or emperor penguin in Antarctica are projected to decline because of climate-induced changes in oceanographic conditions, such as temperature and upwelling intensity (Wolf et al., 2010; see also Box CC-UP), or summer sea ice conditions (Jenouvrier et al., 2012). The diversity of megafaunal responses to climate change will have cascading ecosystem impacts, and will affect ecosystem services such as tourism (*high confidence*; Sections 6.3.7, 6.4.1).

6.5.3. Ecosystems and Fisheries

One of the most direct impacts of climate change on marine ecosystem services is through fisheries (Sections 6.4.1, 7.2.1.2, 7.3.2.4, 7.4.2). Projected climate impacts on fisheries are based on recruitment, growth, mortality, abundance, and distribution of fish stocks as well as changes in ocean NPP (Cheung et al., 2008), evaluated from chlorophyll concentration and other variables such as sea surface temperature (Campbell et al., 2002). Friedland et al. (2012) suggested that chlorophyll concentration, indicating both phytoplankton production and biomass, is a better predictor of the fishery yield in large marine ecosystems than NPP. While the principle holds that catch potential is dependent on energy from primary production, quantitative projections of catch potential are limited by residual uncertainty on the best possible indicators of primary production and biomass.

Assuming that the potential fish catch is proportional to NPP, the fish catch in the North Pacific Ocean subtropical biome is projected to increase by 26% through expansion of the biome, while catches in the temperate and equatorial biomes may decrease by 38 and 15%, respectively, through contraction of the biomes by 2100 relative to 2000 under the SRES A2 (RCP6.0 to 8.5) scenario (Polovina et al., 2011). Changes in phytoplankton size structure are projected to affect fisheries catch potential (Cheung et al., 2011), resulting in a 0 up to 75.8% decrease in the potential catch of large fishes in the central North Pacific

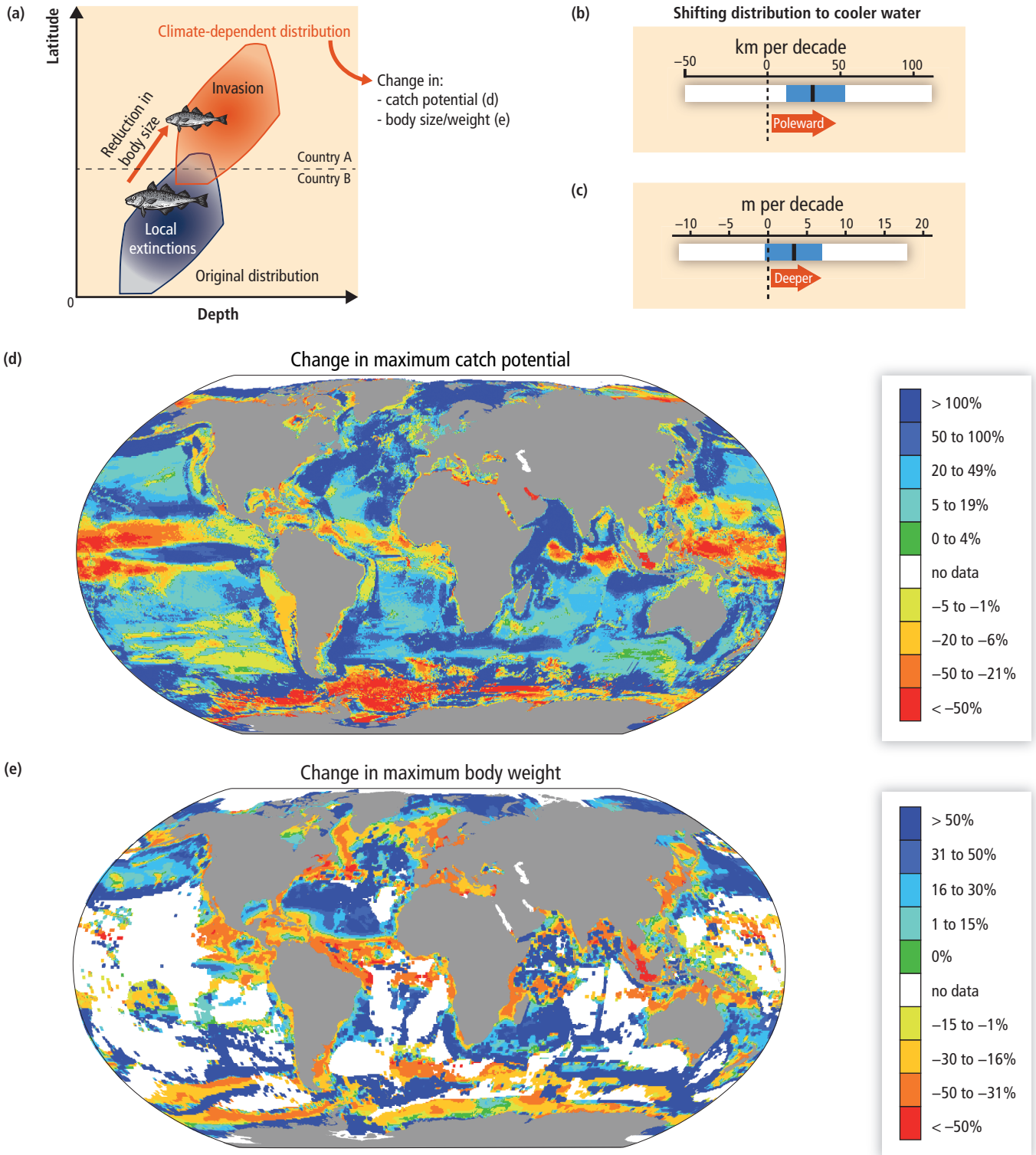


Figure 6-14 | Climate change effects on the biogeography, body size, and fisheries' catch potential of marine fishes and invertebrates. (a) Shifts in distribution range and reduction in body size of exploited fish driven by projected warming, oxygen depletion, and sea ice retreat (cf. Figure 6-7). Whenever the shift in distribution does not fully compensate for warming and hypoxia, the result will be a decrease in body size. Shifts in (b) latitudinal and (c) depth distribution of 610 exploited demersal fishes are projected to have a median (central line of the box) of 31 km per decade and 3.3 m per decade, respectively, with variation between species (box boundary: 25th and 75th percentiles) from 1991–2010 to 2041–2060 under the SRES A2 (between RCP6.0 and 8.5) scenario (Cheung et al., 2011, 2013b). (d) Combining species' range shifts with projected changes in net primary production leads to a projected global redistribution of maximum catch potential. (Analysis includes approximately 1000 species of exploited fishes and invertebrates, under warming by 2°C according to SRES A1B (≈RCP6.0), comparing the 10-year averages 2001–2010 and 2051–2060; redrawn from Cheung et al., 2010.). (e) Changes in species distribution and individual growth are projected to lead to reduced maximum body size of fish communities at a certain site. The analysis includes 610 species of marine fishes, from 1991–2010 to 2041–2060 under SRES A2 (approximately RCP6.0 to 8.5; Cheung et al., 2013b), without analysis of potential impacts of overfishing or ocean acidification. Key assumptions of the projections are that current distribution ranges reflect the preferences and tolerances of species for temperature and other environmental conditions and that these preferences and tolerances do not change over time. Catch potential is determined by species range and net primary production. Growth and maximum body size of fishes are a function of temperature and ambient oxygen level.

and increases of up to 43% in the California Current region over the 21st century under the SRES A2 scenario (Woodworth-Jefcoats et al., 2013). Globally, climate change is projected to cause a large-scale redistribution of global catch potential, with an average 30 to 70% increase in yield at high latitudes and up to 89% in some regions, after 2°C warming from preindustrial periods following SRES A1B (≈RCP6.0) (Cheung et al., 2010; Blanchard et al., 2012; see also Figure 6-14). Redistribution between areas, with average catch potential remaining unchanged, will occur at mid latitudes. A 40 to 60% drop will occur in the tropics and in Antarctica by the 2050s relative to the 2000s (*medium confidence* for direction of trends in fisheries yields, *low confidence* for the magnitude of change). This highlights high vulnerabilities in the economies of tropical coastal countries (Allison et al., 2009; see also Section 6.4).

Fisheries targeting specific species may show more complex responses to climate change. For example, driven by changes in temperature and primary production, catches of skipjack and bigeye tuna in the south Pacific are projected to increase by 2035 relative to 1980–2000 under the SRES B1 and A2 scenario, but for 2100, skipjack tuna catch is projected to decrease under the A2 scenario, while bigyeye tuna catch decreases under both A2 and B1 scenarios (Lehodey et al., 2011). Regionally, tuna catches in the Western Pacific are projected to decrease, while those in the Eastern Pacific will increase (Lehodey et al., 2011). Mollusk fisheries under ocean acidification is discussed under Section 6.4.1.

Identifying responses to climate change is complicated by species interactions and multiple stressors. Major marine habitats and biodiversity hotspots are projected to encounter cumulative impact from changes in temperature, pH, oxygen, and primary productivity by the end of the 21st century (RCP4.5 and 8.5) (Mora et al., 2013). Acidification and hypoxia will reduce maximum catch potential over 50 years from about 2000 onward in both the North Atlantic and Northeast Pacific (Ainsworth et al., 2011; Cheung et al., 2011). Changes in O_2 content as well as warming will drive a global decrease of community-averaged maximum body size of 14 to 24% of exploited demersal marine fishes by 2050 relative to the 2000s under the SRES A2 (RCP6.0 to 8.5) scenario (Cheung et al., 2013b; see also Figure 6-14). The decrease in maximum body size may affect natural mortality rates and trophic interactions, and reduce yield-per-recruit and thus potential catch. Responses of exploited marine species and their fisheries may interact with other human stressors such as overfishing, exacerbating their impacts (e.g., Lindegren et al., 2010; Ainsworth et al., 2011). Through species shifts climate change may also cause overlap of habitats of species targeted by fishing with habitat of threatened species, potentially increasing the chances of the latter of being caught as bycatch (Jones et al., 2013). Moreover, differences in vulnerability and adaptive capacity of species to changing environmental and ecosystem conditions will affect the responses of fisheries to climate change (e.g., Le Borgne et al., 2011; Griffith et al., 2011).

The complex and nonlinear interactions and responses of both biophysical and socioeconomic systems to climate change may lead to changes that have a low probability of occurrence based on empirical data (Doak et al., 2008). The risk of such low-probability but potentially high-impact events may be underestimated in existing model projections (Williams and Jackson, 2007; Lindenmayer et al., 2010). Projected changes in the distribution and production potential of fisheries resources are expected to affect economics, human livelihood, and food security (Allison et al., 2009; Sumaila and Cheung, 2010; *low confidence* in the magnitude and direction of the projected socioeconomic impacts).

6.5.4. Conclusions

Modeling projects that the distribution of invertebrates, fishes, and some marine mammals, birds, and reptiles will shift further under most emission scenarios, with rates and directions of shifts consistent with those observed in the last century (*high confidence*; Sections 6.3.1-7). These projections are valid for those species that adapt not at all or incompletely to warmer temperatures and the associated ecosystem changes, as indicated by present trends (Section 6.3.1; Box CC-MB). For non-adapting species rates of shift will thus increase with increasing rates of warming and higher emission scenarios (*high confidence*), unless the shift is blocked by geographic or other barriers (e.g., light regime; Figure 6-7). The average shift in distribution will continue to be poleward at large spatial scales (*high confidence*; Section 6.5.2; Box CC-MB). Species richness and the abundance of warm-water species will increase at high latitudes (*high confidence*) and decrease in the tropics (*medium confidence*; Section 6.5.2). Projections for individual species and populations are more variable and sensitive to model parameters.

Maximum fisheries catch potential is projected to increase at high and decrease at low latitudes by 2050 under SRES B1 (≈RCP4.5) and A1B (≈RCP6.0) climate scenarios (*medium confidence*; Section 6.5.3). Quantifying such projections is constrained by uncertainties in projected primary production rates (Sections 6.3.4, 6.5.1), biological responses such as species interactions (Section 6.3.6), and in projected effects of multiple climate drivers and human activities (*low confidence*; Section 6.3.5).

Models that integrate climate and ocean changes with biological responses and interactions, and with current human activities, have led to agreement on species and food web responses to climate change (Section 6.5.3). However, most of these models do not include trophic interactions. They insufficiently consider physiological principles and none include evolutionary adaptations that affect responses of biota to physical and chemical changes.

Projections of ocean biogeochemistry represent the open oceans rather well, but coastal and shelf regions only poorly. From a global perspective, open ocean NPP will decrease moderately by 2100 under both medium (SRES B1 or RCP4.5) and high emission scenarios (*medium confidence*; A2 or RCP6.0 to 8.5; Sections 6.3.4, 6.5.1), paralleled by an increase in NPP at high latitudes and a decrease in the tropics (*medium confidence*; Sections 6.3.4, 6.5.1; Box CC-PP).

Overall, the projected responses of marine organisms and ecosystems to climate change include changes in primary productivity (*medium confidence*), species' life history (*medium confidence*), distribution, abundance, and diversity across marine food webs (*high confidence*) in a time frame of 20 to 80 years from 2010, with substantially larger

long-term (end of 21st century) responses under high emission scenarios (*high confidence*). These changes will be largest under business-as-usual scenarios (RCP8.5) and increase the vulnerability of human societies, by affecting income, employment, and food security through their effects on fisheries, tourism, and regulatory services such as coastal protection (*medium confidence*; Section 6.4.1.3; Box CC-CR).

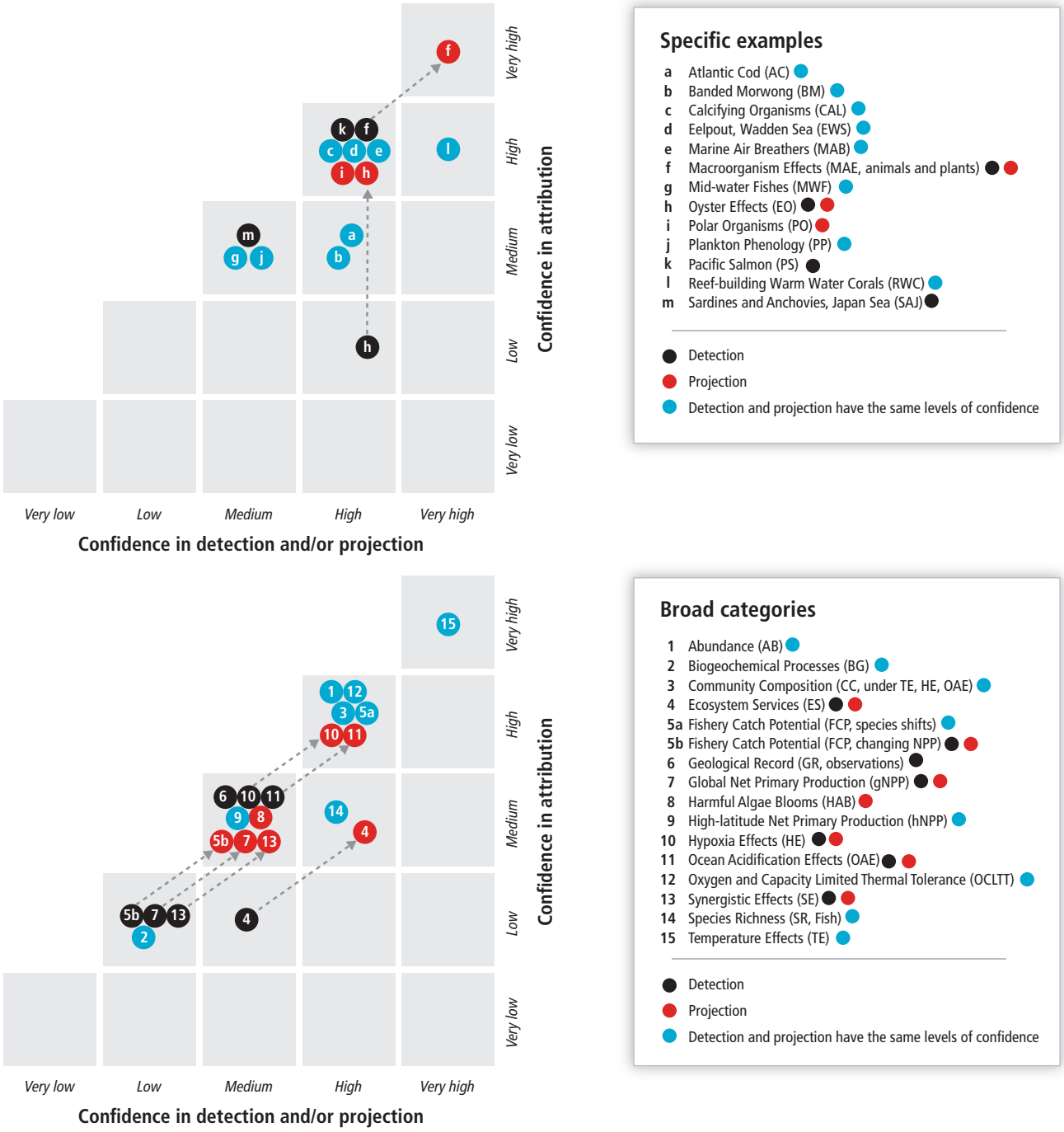


Figure 6-15 | Overview of the levels of confidence in detection, as well as in projection, of climate change effects on ocean systems, in relation to the levels of confidence in attributing these effects to the respective climate forcings. Case studies, processes, and concepts relevant in assessing the effects of climate change are represented by their acronyms in both text and figure. While confidence in the presence of effects is often high, the direct attribution to one driver in field experiments is difficult, as drivers are often highly correlated with each other (e.g., warming with changes in stratification, hence reduced nutrient supply). Some climate change impacts have been condensed into broad categories to avoid overpopulating the figures (e.g., Bio-Geochemical processes, BG). Note that the term "attribution" is used for both present-day detections in the field and future projections, the latter including qualitative and quantitative extrapolations and simulations of future conditions from fundamental principles, experiments, and models. Firm knowledge from experiments (field, laboratory, and modeling) simulating future conditions enhances the respective confidence levels to those for detection or projection. The empirical observations resulting from those experiments are directly attributable to the respective drivers. Confidence in attribution is enhanced if these experiments identify the underlying mechanisms and their responses. See text for the discussion of depicted examples and categories. Confidence assignments focus on the nature and size of effects, not on model capacity to quantify their magnitude reliably.

6.6. Chapter Conclusions and Key Uncertainties

This section provides an overview of confidence levels in the detection and projection of climate change effects on ocean systems, and of confidence levels in their attribution to different forcings. It distinguishes between effects previously observed and those projected, and considers confidence in the knowledge of underlying principles as discussed in this chapter. While the anthropogenic signal is conspicuous in the oceans (Section 6.1.1), clear attribution to anthropogenic influences on climate is not always possible in individual case studies, owing to the inherent variability of the system (Figure 6-15; acronyms of relevant processes, capitalized, link between text and figure).

Present-day observations and those from the Geological Record (GR; Figure 6-15) show similar signs of response to environmental changes, for example, warming at high CO_2 levels, and similar ecological consequences in the ocean (*robust evidence*, *medium agreement*; *medium confidence*). However, the ongoing rate of anthropogenic CO_2 release and hence ocean acidification is unprecedented in the last 65 Ma (*high confidence*) and probably the last 300 Ma (Section 6.1.2).

6.6.1. Key Risks Related to Climate Change: Constraints on Ecosystem Services

Empirical studies provide evidence that climate change has impacted marine ecosystems (*high confidence*; FAQ 6.4; Table 6-6) and has caused changes in provisioning, regulating, and supportive Ecosystem Services (ES; *medium confidence*). Climate change may also have affected cultural services (*limited evidence*, *medium agreement*) but attribution of impacts to these services remains a challenge (*low confidence*), owing to the intrinsic difficulties of assessing these services, the lack of long time-series data, and confounding human impacts. In light of available understanding of cause and effect of climate change impacts on marine ecosystems (*high confidence*), future climate change will affect some ecosystem services (*high confidence* in projection, *medium confidence* in attribution). Projected changes in the availability of marine resources and ecosystem services are expected to affect economics, human livelihood, and food security. Vulnerability is highest for the national economies of tropical coastal countries (*high confidence*).

6.6.1.1. Redistribution and Constraints on Microbial Functions and Primary Productivity

Laboratory and mesocosm studies have identified various microbially mediated processes responding to climate-induced changes in light, nutrient supply, temperature, CO_2, and hypoxia (*high confidence*). Such processes include nitrogen fixation and the nitrogen cycle, carbon sequestration and export production, calcification, respiration, O_2 production, climate-feedback by dimethylsulfide (DMS) production, and nutrient recycling. However, changes in these Bio-Geochemical processes (BG) in the field are difficult to detect, project, and attribute to climate change (*low confidence*; Sections 6.3.1-5).

The trends in net primary production recently reported for much of the low-latitude ocean using satellite observations differ considerably from those few long-term direct estimates of NPP at oceanic time series sites (Sections 6.1.2, 6.3.4). Increased NPP at high latitudes (hNPP, detected and attributable to climate change with *medium confidence*; Section 6.3.4; Box CC-PP) are indicated by satellite images (*medium confidence*) and due to reduction and thinning of sea ice. Trends in NPP will be strengthened with further warming (*medium confidence*). Modeling projects that global NPP (gNPP) will decrease by 2100 under RCP scenarios (*medium confidence*; Section 6.5.1; Box CC-PP).

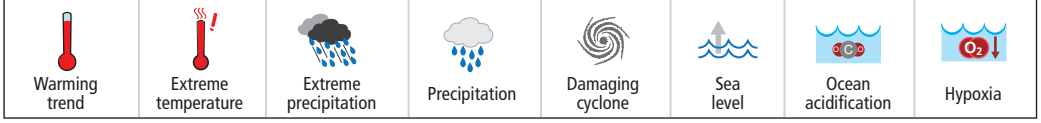
6.6.1.2. Warming-Induced Species Redistribution, Loss of Biodiversity, and Fisheries Catch Potential

Long-term observations show variability in oceanographic conditions with a key role of temperature and changing oceanographic regimes causing observed changes in ecosystem structure and fish stocks (*very high confidence*; cf. Section 30.7.1.1). Temperature Effects (TE) reflect the differential specialization of all life forms in limited ambient temperature ranges (*very high confidence*). Temperature exerts strong MAcroorganism Effects (MAE), that is, on animals and plants. Warming is presently causing and will cause species displacements and largely poleward shifts in biogeographic distribution of zooplankton and fishes, paralleled by altered seasonal activity, species abundance, migration, and body size (*high* to *very high confidence*; Section 6.3.1), and leading to shifts in Community Composition (CC; *high confidence*; Box 6-1). Causes and effects are understood for fishes and most invertebrates via their Oxygen and Capacity Limited Thermal Tolerance (OCLTT; *robust evidence*, *medium agreement*; *high confidence*; Section 6.3.1). Such knowledge supports projections into the future (*high confidence*; Section 6.5), which are influenced by the limited potential of organisms to adapt. Alterations in species ABundance (AB) result when organisms encounter shifting mean and extreme temperatures (*high confidence* in detection and attribution). Such trends will be exacerbated during future warming (*high confidence*; Section 6.5.1).

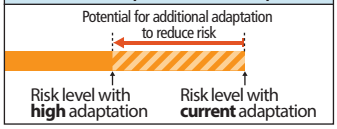
Among prominent examples, warming has caused and will cause northward shift and expansion of the geographic distribution of North Atlantic Cod (AC; *high confidence* in detection or projection, *medium confidence* in detection or projection and attribution; Section 6.3.1) and shifting growth patterns in relation to the distribution of Banded Morwong around New Zealand (BM; *high confidence* in detection or projection, *medium confidence* in detection or projection and attribution). Warming has shifted dominant species from Sardines to Anchovies in the Sea of Japan (SAJ; *medium confidence* in detection, *medium confidence* in detection and attribution; Sections 6.3.1, 6.3.6). Warming extremes have reduced and will further reduce the abundance of Eelpout in the Wadden Sea (EWS; *high confidence* in detection or projection, *high confidence* in detection or projection and attribution; Section 6.3.1). Extreme warming events increase mortalities of Pacific Salmon during spawning migrations (PS; *high confidence* in detection, *high confidence* in detection and attribution; Section 6.3.1) in Fraser River, Canada. At temperate and high latitudes, communities display increasing fish Species Richness (SR) resulting from latitudinal shifts of species and attributed to warming and loss of sea ice, although the relative contributions of regional climate variation and long-term global trends have not been quantified (*high confidence* in detection, *medium confidence* in detection and attribution; Sections 6.3.1, 6.5.2). Latitudinal species shifts are

Table 6-6 | Coastal and oceanic key risks from climate change and the potential for risk reduction through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments made by authors of the various WGII AR5 chapters, with supporting evaluation of evidence and agreement in the referenced chapter sections. Each key risk is characterized as *very low*, *low*, *medium*, *high*, or *very high*. Risk levels are presented for the near-term era of committed climate change (here, for 2030–2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer-term era of climate options (here, for 2080–2100), for global mean temperature increase of 2°C and 4°C above pre-industrial levels. For each time frame, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. As the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks. Relevant climate variables are indicated by symbols. Acronyms for oceans sub-regions are as follows: HLSBS = High-Latitude Spring Bloom Systems; EUS = Equatorial Upwelling Systems; SES = Semi-Enclosed Seas; CBS = Coastal Boundary Systems; EBUE = Eastern Boundary Upwelling Ecosystems; STG = Sub-Tropical Gyres, DS = Deep Sea (>1000 m).

Climate-related drivers of impacts



Level of risk & potential for adaptation



Risks to ecosystems and adaptation options

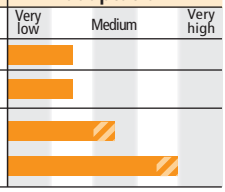
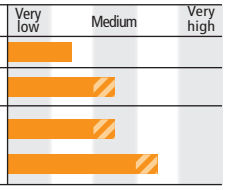
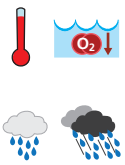
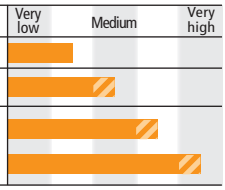
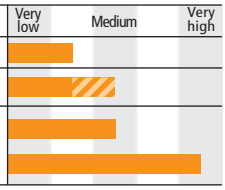
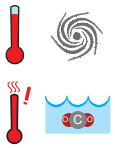
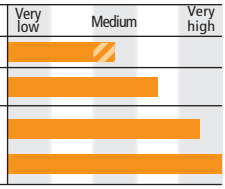
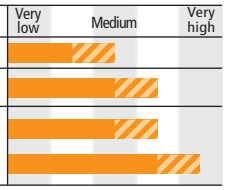
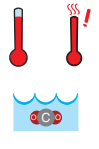
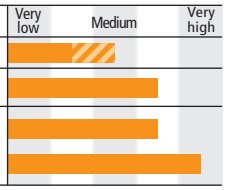
Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Changes in ecosystem productivity associated with the redistribution and loss of net primary productivity in open oceans. (*medium confidence*) [6.5.1, 6.3.4, 30.5.1-2, Box CC-PP]	Adaptation options are limited to the translocation of industrial fishing activities due to regional decreases (low latitude) versus increases (high latitude) in productivity, or to the expansion of aquaculture.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Distributional shift in fish and invertebrate species, fall in fisheries catch potential at low latitudes, e.g., in EUS, CBS, and STG regions. (*high confidence*) [6.3.1, 6.5.2-3, 30.5.1-4, 30.6.2, Box CC-MB]	Evolutionary adaptation potential of fish and invertebrate species to warming is limited as indicated by their changes in distribution to maintain temperatures. Human adaptation options involve the large-scale translocation of industrial fishing activities following the regional decreases (low latitude) versus (possibly transient) increases (high latitude) in catch potential as well as deploying flexible management that can react to variability and change. Further options include improving fish resilience to thermal stress by reducing other stressors such as pollution and eutrophication, the expansion of sustainable aquaculture and development of alternative livelihoods in some regions.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
High mortalities and loss of habitat to larger fauna including commercial species due to hypoxia expansion and effects. (*high confidence*) [6.3.3, 30.5.3-5]	Human adaptation options involve the large-scale translocation of industrial fishing activities as a consequence of the hypoxia-induced decreases in biodiversity and fisheries catch of pelagic fish and squid. Special fisheries may benefit (Humboldt squid). Reducing the amount of organic carbon running off coastlines by controlling nutrients and pollution running off agricultural areas can reduce microbial activity and consequently limit the extent of the oxygen drawdown and the formation of coastal dead zones.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Ocean acidification: Reduced growth and survival of commercially valuable shellfish and other calcifiers, e.g., reef building corals, calcareous red algae. (*high confidence*) [5.3.3.5, 6.1.1, 6.3.2, 6.4.1.1, 30.3.2.2, Box CC-OA]	Evidence for differential resistance and evolutionary adaptation of some species exists but is likely limited by the CO_2 concentrations and high temperatures reached; adaptation options include the shift to exploiting more resilient species or the protection of habitats with low natural CO_2 levels, as well as the reduction of other stresses, mainly pollution and limiting pressures from tourism and fishing.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Reduced biodiversity, fisheries abundance and coastal protection by coral reefs due to heat-induced mass coral bleaching and mortality increases, exacerbated by ocean acidification, e.g., in CBS, SES, and STG regions. (*high confidence*) [5.4.2.4, 6.3.1, 6.4.2, 30.3.1.1, 30.3.2.2, 30.5.3-6, Box CC-CR]	Evidence of rapid evolution by corals is very limited or nonexistent. Some corals may migrate to higher latitudes. However, the movement of entire reef systems is unlikely given estimates that they need to move at the speed of 10 – 20 km yr^{-1}. Human adaptation options are limited to reducing other stresses, mainly enhancing water quality and limiting pressures from tourism and fishing. This option will delay the impacts of climate change by a few decades but is likely to disappear as thermal stress increases.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Coastal inundation and habitat loss due to sea level rise, extreme events, changes in precipitation, and reduced ecological resilience, e.g., in CBS and STG subregions. (*medium to high confidence*) [5.4.2.3-7, 5.5.2, 5.5.4, 30.5.6, Box CC-CR]	Options to maintain ecosystem integrity are limited to the reduction of other stresses, mainly pollution and limiting pressures from tourism, fishing, physical destruction, and unsustainable aquaculture; reducing deforestation and increasing reforestation of river catchments and coastal areas to retain sediments and nutrients; increased mangrove, coral reef, and seagrass protection and restoration to protect numerous ecosystem goods and services such as coastal protection, tourist value, and fish habitat.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Marine biodiversity loss with high rate of climate change. (*medium confidence*) [6.3.1-3, 6.4.1.2-3, Table 30.4, Box CC-MB]	Adaptation options are limited to the reduction of other stresses, mainly to reducing pollution and to limiting pressures from tourism and fishing.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	

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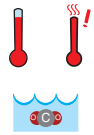
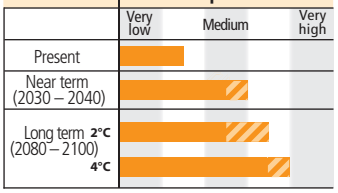
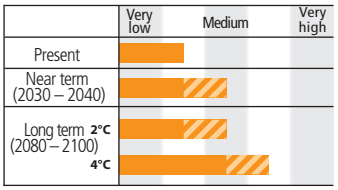
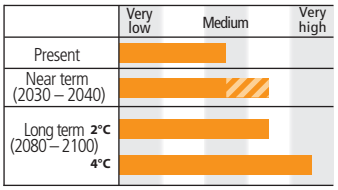
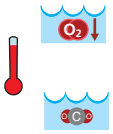
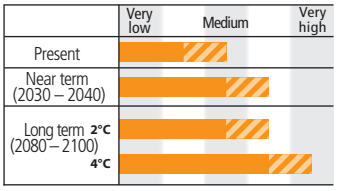
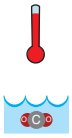
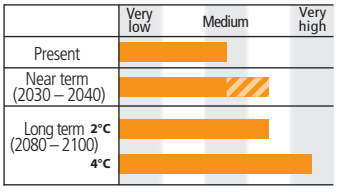
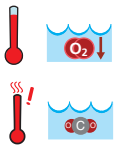
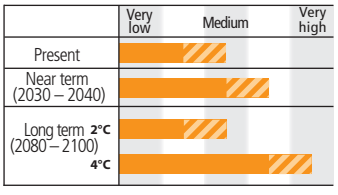
Table 6-6 (continued)

Risks to fisheries				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Decreased production of global shellfish fisheries. (*high confidence*) [6.3.2, 6.3.5, 6.4.1.1, 30.5.5, 30.6.2.1, Box CC-OA]	Effective shift to alternative livelihoods, changes in food consumption patterns, and adjustment of (global) markets.			
Global redistribution and decrease of low-latitude fisheries yields are paralleled by a global trend to catches having smaller fishes. (*medium confidence*) [6.3.1, 6.4.1, 6.5.3, 30.5.4, 30.5.6, 30.6.2]	Increasing coastal poverty at low latitudes as fisheries becomes smaller – partially compensated by the growth of aquaculture and marine spatial planning, as well as enhanced industrialized fishing efforts.			
Redistribution of catch potential of large pelagic-highly migratory fish resources, such as tropical Pacific tuna fisheries. (*high confidence*) [6.3.1, 6.4.3, Table 30.4]	International fisheries agreements and instruments, such as the tuna commissions, may have limited success in establishing sustainable fisheries yields.			
Variability of small pelagic fishes in Eastern Boundary Upwelling systems is becoming more extreme at interannual to multi-decadal scales, making industry and management decisions more uncertain. (*medium confidence*) [6.3.2, 6.3.3, 30.5.5, Box CC-UP]	Development of new and specific management tools and models may have limited success to sustain yields. Reduction in fishing intensity increases resilience of the fisheries.			
Decrease in catch and species diversity of fisheries in tropical coral reefs, exacerbated by interactions with other human drivers such as eutrophication and habitat destruction. (*high confidence*) [6.4.1, 30.5.3-4, 30.5.6, Table 30-4, Box CC-CR]	Restoration of overexploited fisheries and reduction of other stressors on coral reefs delay ecosystem changes. Human adaptation includes the usage of alternative livelihoods and food sources (e.g., coastal aquaculture).			
Current spatial management units, especially the MPAs, may fail in the future due to shifts in species distribution and community structure. (*high confidence*) [6.3.1, 6.4.2.1, 30.5.1, Box CC-MB]	Continuous revision and shifts of MPA borders, and of MPA goals and performance.			

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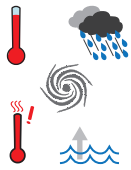
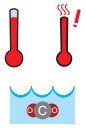
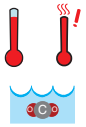
projected to continue in the 21st century under all IPCC emission scenarios (*high confidence*; Sections 6.3.1, 6.3.5, 6.3.7, 6.4.1, 6.5.2).

Climate-induced regime shifts and regional changes in Plankton Phenology (PP; *medium confidence*) have caused and will cause changes in food composition and availability to animals. Species shifts and changing species composition lead to changes in Fishery Catch Potential (FCP; *high confidence*; 5a in Figure 6-15), partly attributable to climate change (*high confidence*) and to sustained fishing pressure (Section 6.5.3). Fisheries Catch Potentials (FCP) will be redistributed, decrease at low latitudes, and increase at high latitudes (*high confidence*; 5a in Figure 6-15). These trends will possibly be strengthened by the projected decrease in NPP at low latitudes and increase in NPP at high latitudes (*medium confidence*; Sections 6.5.2-3; 5b in Figure 6-15). Polar Organisms (PO) that are unable to migrate to cooler waters, and to acclimatize or to adapt to warming, will become marginalized, contributing to the projected high species turnover in polar areas (*high confidence*; Sections 6.3.1, 6.5.2).

Detected effects on Marine Air Breathers (MAB: mammals, seabirds, and reptiles) include changing abundances and phenology, shifts in species distribution, and in sea turtle sex ratios (*high confidence*), all of which are partly attributed to climate change (*high confidence*). However, few effects are directly linked to climate drivers (e.g., temperature-driven turtle sex ratio); most effects are due to shifts in habitat structure (e.g., loss of sea ice), changing availability of prey organisms, or changes in

Table 6-6 (continued)

Risks to humans and infrastructure				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Coastal socioeconomic security. (*high confidence*) [5.5.2, 5.5.4, 30.6.5, 30.7.1, Table 30-4]	Human adaptation options involve (1) protection using coastal defences (e.g. seawalls) and soft measures (e.g., mangrove replanting and enhancing coral growth); (2) accommodation to allow continued occupation of coastal areas by making changes to human activities and infrastructure; and (3) managed retreat as a last viable option. Options vary from large-scale engineering works to smaller scale community projects. Options are available under the more traditional CZM (coastal zone management) framework but increasingly under DRR (disaster risk reduction) and CCA (climate change adaptation) frameworks.		Present Near term (2030 – 2040) Long term 2°C (2080 – 2100) 4°C	Very low / Medium / Very high * Present * Near term * Long term 2°C * 4°C
	**High confidence* in existence of adaptation measures, *Low confidence* in magnitude of risk reduction			
Reduced livelihoods and increased poverty. (*medium confidence*) [6.4.1-2, 30.6.2, 30.6.5]	Human adaptation options involve the large-scale translocation of industrial fishing activities following the regional decreases (low latitude) versus increases (high latitude) in catch potential and shifts in biodiversity. Artisanal local fisheries are extremely limited in their adaptation options by available financial resources and technical capacities, except for their potential shift to other species of interest.		Present Near term (2030 – 2040) Long term 2°C (2080 – 2100) 4°C	Very low / Medium / Very high
Impacts due to increased frequency of harmful algal blooms (*medium confidence*) [6.4.2.3, 30.6.3]	Adaptation options include improved monitoring and early warning system, reduction of stresses favoring harmful algal blooms, mainly pollution and eutrophication, as well as the avoidance of contaminated areas and fisheries products.		Present Near term (2030 – 2040) Long term 2°C (2080 – 2100) 4°C	Very low / Medium / Very high
Impacts on marine resources threatening regional security as territorial disputes and food security challenges increase (*limited evidence, medium agreement*) [AR5 SREX, 30.6.5, 30.7.2, 12.4-6, 29.3]	Decrease in marine resources, movements of fish stocks and opening of new seaways , and impacts of extreme events coupled with increasing populations will increase the potential for conflict in some regions, drive potential migration of people, and increase humanitarian crises.		Present Near term (2030 – 2040) Long term 2°C (2080 – 2100) 4°C	Very low / Medium / Very high
Impacts on shipping and infrastructure for energy and mineral extraction increases as storm intensity and wave height increase in some regions (e.g., high latitudes) (*high confidence*) [AR5 SREX, 30.6.2.3-4, 30.6.5, 29.3]	Adaptation options are to limit activities to particular times of the year and/or develop strategies to decrease the vulnerability of structures and operations.		Present Near term (2030 – 2040) Long term 2°C (2080 – 2100) 4°C	Very low / Medium / Very high

foraging efficiency, in both mammals (polar bears, walruses) and birds (penguins, albatrosses). Such trends will be exacerbated by future warming (*high confidence*; Sections 6.3.7, 6.5.2).

6.6.1.3. Expanding Hypoxia Affecting Marine Resources

Hypoxic zones in marine sediments and pelagic OMZs will continue to expand in the future, owing to climate-induced warming trends (Section 6.1.1). Local and regional Hypoxia Effects (HE) have been observed (*medium confidence*) and will be exacerbated in the future (*high confidence*; Section 6.3.3) causing habitat loss for groundfishes and pelagic predators and affecting the distribution of key zooplankton and nekton species (*medium confidence*). Progressive hypoxia is causing shifts in community composition toward hypoxia-tolerant species, excluding calcifiers due to elevated pCO_2 (*high confidence*), benefiting specialized microbes, and leading to reduced biodiversity and the loss of higher life forms (*high confidence*; Section 6.3.3). Loss of deep habitat and biomass of Mid-Water Fishes (MWF; Section 6.3.3; *medium confidence* in detection) off California is also attributed to hypoxia (*medium confidence*). These trends will continue into the future (*medium confidence*).

6.6.1.4. Constraints on Marine Calcifiers and Associated Fisheries and Aquaculture due to Ocean Acidification

Ocean acidification will exert negative effects on species and whole ecosystems and their services, especially those relying on carbonate structures such as warm-water coral reefs (*high confidence*; cf. Section 30.7.1.2). Presently, only a small number of field observations have detected Ocean Acidification Effects (OAE; *medium confidence*), but experiments and natural analogs support reliable but qualitative projections and attribution (*high confidence*). A specific glimpse into the future of anthropogenic OA is provided by negative Effects of upwelled CO_2-rich waters on Pacific Oysters (EO) introduced to aquaculture along the North American west coast (*high confidence* in detection, *low confidence* in attribution to anthropogenic causes). Findings in experimental laboratory and field studies as well as at natural analogs support attribution of projected effects to future CO_2

concentrations (*medium confidence*), with species-specific sensitivities across phyla (*high confidence*). Projected effects are most harmful to strong CALcifiers (CAL; *high confidence*), for example, some echinoderms, bivalves, gastropods, warm-water corals, and crustose algae, and less harmful to some crustaceans and, possibly, fishes. Projections from experimental studies and observations at natural analogs indicate shifts in Community Composition (CC) to more active animals and from calcifiers (CAL) to non-calcifiers in all organism groups (*high confidence* in both projection and attribution to increased CO_2; Section 6.3.2; Table 6-3).

6.6.1.5. Interactions of Climate-Related Drivers Exacerbating Impacts on Organisms, Ecosystems, and Their Services

Climate change involves interactions of temperature with other climate-related drivers and their effects (ocean acidification, hypoxia, freshening, nutrient supply, organism shifts resulting in changing interactions between species, changes in habitat structure, e.g., loss of sea ice). Strong interactions with other human impacts like eutrophication, fishing, and other forms of harvesting accelerate and amplify climate-induced changes (*high confidence*; Section 6.3.5, 30.7.1.1). Harmful algal blooms (HAB) will be stimulated by warming, nutrient fluctuations in upwelling areas, eutrophication in coastal areas (Table 6-6), ocean acidification, and enhanced surface stratification (*medium confidence*). Synergistic Effects (SE) will be exacerbated in the future (*medium confidence*), but have not yet been clearly detected and attributed in the field (*low confidence*). For projected future effects, attribution of observed impacts to such synergisms is supported by experimental evidence, especially in animals and plants (*medium confidence*).

Increased bleaching and decreased calcification displayed by several Reef-building Warm-water Corals (RWC; *very high confidence*) over the last 3 decades are attributed to the ongoing warming trend, and the associated rise in extreme temperature events and amplitudes (*high confidence*; Sections 6.3.1, 30.5.6; Box CC-CR). Such trends will be exacerbated by future warming and synergistic effects (*high confidence*; cf. Section 30.5.4.2), with some amelioration by latitudinal shifts and evolutionary adaptation (Section 6.3.1; *low confidence*). Ocean acidification will have an increasing influence on reefs (*high confidence*), as indicated by similar phenomena during mass extinctions in Earth history.

6.6.2. Key Uncertainties

Key uncertainties result from insufficient knowledge of ocean systems. International organizations (both inter- and non-governmental) have the opportunity to play a key role in coordinating research concepts and approaches, working toward a coherent picture of climate change effects on the global ocean. Countries around the world have limited capacity and infrastructure to study the ocean's response to climate change. Long-term observational time series are especially lacking, in both quantity and quality. Research has provided valuable insights, but a unifying approach addressing principles across organism domains and ecosystems is still missing. Processes investigated so far differ largely by study organisms (plants, animals, phytoplankton, and bacteria) and by level of organization (ecosystem, whole organism, tissue, cell, molecular). Especially for microbes, available data are patchy and reported trends are often in different directions, partly due to different experimental protocols and/or over-reliance on species or strains of microbes that are readily culturable, and hence have been used for decades in laboratory research. The knowledge base of climate impacts on species, strains, or communities in the field is insufficient. Scaling from physiological studies on individual species to ecosystem changes has been successful in individual cases but has not been widely implemented, for example, to shifts in species interactions or food webs. An integrated framework of climate sensitivity at the ecosystem level that considers multiple drivers and their interactive effects needs to be developed further. This includes an in depth understanding of ecosystem structure (physical and biological) and functioning, of ecosystem complexity and species interactions, and of the resulting implications for biogeochemical processes. For all climate drivers, especially ocean warming, acidification, and hypoxia, studies integrating mechanistic knowledge and evolutionary adaptation over generations are needed. Research should also cover various climate zones and biomes. Laboratory and modeling experiments are needed to test hypotheses building on long-term field observations and observations at natural or paleo-analogs. Models should better integrate observations and mechanism-based understanding, and better project future interactions between human and natural systems in a changing climate.

References

Abed, R.M., F. Garcia-Pichel, and M. Hernandez-Marine, 2002: Polyphasic characterization of benthic, moderately halophilic, moderately thermophilic cyanobacteria with very thin trichomes and the proposal of *Halomicronema excentricum* gen. nov., sp. nov. *Archives of Microbiology*, **177(5)**, 361-370.

Adger, W.N., T.P. Hughes, C. Folke, S.R. Carpenter, and J. Rockström, 2005: Social-ecological resilience to coastal disasters. *Science*, **309(5737)**, 1036-1039.

Ainsworth, C.H., J.F. Samhouri, D.S. Busch, W.W.L. Cheung, J. Dunne, and T.A. Okey, 2011: Potential impacts of climate change on Northeast Pacific marine foodwebs and fisheries. *ICES Journal of Marine Science*, **68(6)**, 1217-1229.

Alheit, J., T. Pohlmann, M. Casini, W. Greve, R. Hinrichs, M. Mathis, K. O'Driscoll, R. Vorberg, and C. Wagner, 2012: Climate variability drives anchovies and sardines into North Sea and Baltic Sea. *Progress in Oceanography*, **96(1)**, 128-139.

Alker, A.P., G.W. Smith, and K. Kim, 2001: Characterization of *Aspergillus sydowii* (Thom et Church), a fungal pathogen of Caribbean sea fan corals. *Hydrobiologia*, **460**, 105-111.

Allison, E.H., A.L. Perry, M.-C. Badjeck, W.N. Adger, K. Brown, D. Conway, A.S. Halls, G.M. Pilling, J.D. Reynolds, N.L. Andrew, and N.K. Dulvy, 2009: Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries*, **10(2)**, 173-196.

Altizer, S., R.S. Ostfeld, P.T.J. Johnson, S. Kutz, and C.D. Harvell, 2013: Climate change and infectious diseases: from evidence to a predictive framework. *Science*, **341(6145)**, 514-519.

Amelung, B., S. Nicholls, and D. Viner, 2007: Implications of global climate change for tourism flows and seasonality. *Journal of Travel Research*, **45(3)**, 285-296.

Andersson, A.J., F.T. Mackenzie, and J.-P. Gattuso, 2011: Effects of ocean acidification on benthic processes, organisms, and ecosystems. In: *Ocean Acidification* [Gattuso, J.-P. and L. Hansson (eds.)]. Oxford University Press, Oxford, UK, pp. 122-153.

Angilletta, M.J.J., 2009: *Thermal Adaptation. A Theoretical and Empirical Synthesis*. Oxford University Press, Oxford, UK, 320 pp.

Anthony, K.R., D.I. Kline, G. Diaz-Pulido, S. Dove, and O. Hoegh-Guldberg, 2008: Ocean acidification causes bleaching and productivity loss in coral reef builders. *Proceedings of the National Academy of Sciences of the United States of America*, **105(45)**, 17442-17446.

Archer, D., M. Eby, V. Brovkin, A. Ridgwell, L. Cao, U. Mikolajewicz, K. Caldeira, K. Matsumoto, G. Munhoven, A. Montenegro, and K. Tokos, 2009: Atmospheric lifetime of fossil fuel carbon dioxide. *Annual Review of Earth and Planetary Sciences*, **37(1)**, 117-134.

Armbrust, E.V., 2009: The life of diatoms in the world's oceans. *Nature*, **459(7244)**, 185-192.

Armstrong, J.L., J.L. Boldt, A.D. Cross, J.H. Moss, N.D. Davis, K.W. Myers, R.V. Walker, D.A. Beauchamp, and L.J. Haldorson, 2005: Distribution, size, and interannual, seasonal and diel food habits of northern Gulf of Alaska juvenile pink salmon, *Oncorhynchus gorbuscha*. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **52(1-2)**, 247-265.

Arnason, R., 2007: Climate change and fisheries: assessing the economic impact in Iceland and Greenland. *Natural Resource Modeling*, **20(2)**, 163-197.

Arnold, K.E., H.S. Findlay, J.I. Spicer, C.L. Daniels, and D. Boothroyd, 2009: Effect of CO_2-related acidification on aspects of the larval development of the European lobster, *Homarus gammarus* (L.). *Biogeosciences*, **6(8)**, 1747-1754.

Arnold, T., C. Mealey, H. Leahey, A.W. Miller, J.M. Hall-Spencer, M. Milazzo, and K. Maers, 2012: Ocean acidification and the loss of phenolic substances in marine plants. *PLoS ONE*, **7(4)**, e35107, doi:10.1371/journal.pone.0035107.

Arrieta, J.M., S. Arnaud-Haond, and C.M. Duarte, 2010: What lies underneath: conserving the oceans' genetic resources. *Proceedings of the National Academy of Sciences of the United States of America*, **107(43)**, 18318-18324.

Arrigo, K.R. and G.L. van Dijken, 2011: Secular trends in Arctic Ocean net primary production. *Journal of Geophysical Research*, **116(C9)**, C09011, doi:10.1029/2011JC007151.

Arrigo, K.R., D.K. Perovich, R.S. Pickart, Z.W. Brown, G.L. van Dijken, K.E. Lowry, M.M. Mills, M.A. Palmer, W.M. Balch, F. Bahr, N.R. Bates, C. Benitez-Nelson, B. Bowler, E. Brownlee, J.K. Ehn, K.E. Frey, R. Garley, S.R. Laney, L. Lubelczyk, J. Mathis, A. Matsuoka, B.G. Mitchell, G.W.K. Moore, E. Ortega-Retuerta, S. Pal, C.M. Polashenski, R.A. Reynolds, B. Schieber, H.M. Sosik, M. Stephens, and J.H. Swift, 2012: Massive phytoplankton blooms under Arctic sea ice. *Science*, **336(6087)**, 1408.

Auel, H., W. Hagen, W. Ekau, and H.M. Verheye, 2005: Metabolic adaptations and reduced respiration of the copepod *Calanoides carinatus* during diapause at depth in the Angola-Benguela Front and northern Benguela upwelling regions. *African Journal of Marine Science*, **27(3)**, 653-657.

Baker, A.C., 2001: Ecosystems: reef corals bleach to survive change. *Nature*, **411(6839)**, 765-766.

Baker-Austin, C., J.A. Trinanes, N.G.H. Taylor, R. Hartnell, A. Siitonen, and J. Martinez-Urtaza, 2013: Emerging *Vibrio* risk at high latitudes in response to ocean warming. *Nature Climate Change*, **3(1)**, 73-77.

Balazs, G.H. and M. Chaloupka, 2004: Thirty-year recovery trend in the once depleted Hawaiian green sea turtle stock. *Biological Conservation*, **117(5)**, 491-498.

Banse, K., 1991: Rates of phytoplankton cell division in the field and in iron enrichment experiments. *Limnology and Oceanography*, **36(8)**, 1886-1898.

Barange, M., W.W.L. Cheung, G. Merino, and R.I. Perry, 2010: Modelling the potential impacts of climate change and human activities on the sustainability of marine resources. *Current Opinion in Environmental Sustainability*, **2(5-6)**, 326-333.

Barker, S. and H. Elderfield, 2002: Foraminiferal calcification response to glacial-interglacial changes in atmospheric CO_2. *Science*, **297(5582)**, 833-836.

Barker, S., P. Diz, M.J. Vautravers, J. Pike, G. Knorr, I.R. Hall, and W.S. Broecker, 2009: Interhemispheric Atlantic seesaw response during the last deglaciation. *Nature*, **457(7233)**, 1097-1102.

Barton, A., B. Hales, G.G. Waldbusser, C. Langdon, and R.A. Feely, 2012: The Pacific oyster, *Crassostrea gigas*, shows negative correlation to naturally elevated carbon dioxide levels: implications for near-term ocean acidification effects. *Limnology and Oceanography*, **57(3)**, 698-710.

Baumann, H., S.C. Talmage, and C.J. Gobler, 2012: Reduced early life growth and survival in a fish in direct response to increased carbon dioxide. *Nature Climate Change*, **2(1)**, 38-41.

Baumgartner, M., K.O. Stetter, and W. Foissner, 2002: Morphological, small subunit rRNA, and physiological characterization of *Trimyema minutum* (Kahl, 1931), an anaerobic ciliate from submarine hydrothermal vents growing from 28°C to 52°C. *Journal of Eukaryotic Microbiology*, **49(3)**, 227-238.

Bazzino, G., W.F. Gilly, U. Markaida, C.A. Salinas-Zavala, and J. Ramos-Castillejos, 2010: Horizontal movements, vertical-habitat utilization and diet of the jumbo squid (*Dosidicus gigas*) in the Pacific Ocean off Baja California Sur, Mexico. *Progress in Oceanography*, **86(1-2)**, 59-71.

Beare, D., F. Burns, E. Jones, K. Peach, E. Portilla, T. Greig, E. McKenzie, and D. Reid, 2004: An increase in the abundance of anchovies and sardines in the north-western North Sea since 1995. *Global Change Biology*, **10(7)**, 1209-1213.

Beaufort, L., I. Probert, T. de Garidel-Thoron, E.M. Bendif, D. Ruiz-Pino, N. Metzl, C. Goyet, N. Buchet, P. Coupel, M. Grelaud, B. Rost, R.E.M. Rickaby, and C. de Vargas, 2011: Sensitivity of coccolithophores to carbonate chemistry and ocean acidification. *Nature*, **476(7358)**, 80-83.

Beaugrand, G., 2009: Decadal changes in climate and ecosystems in the North Atlantic Ocean and adjacent seas. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **56(8-10)**, 656-673.

Beaugrand, G., P.C. Reid, F. Ibañez, J.A. Lindley, and M. Edwards, 2002: Reorganization of North Atlantic marine copepod biodiversity and climate. *Science*, **296(5573)**, 1692-1694.

Beaugrand, G., M. Edwards, K. Brander, C. Luczak, and F. Ibañez, 2008: Causes and projections of abrupt climate-driven ecosystem shifts in the North Atlantic. *Ecology Letters*, **11(11)**, 1157-1168.

Beaugrand, G., C. Luczak, and M. Edwards, 2009: Rapid biogeographical plankton shifts in the North Atlantic Ocean. *Global Change Biology*, **15(7)**, 1790-1803.

Beaugrand, G., M. Edwards, and L. Legendre, 2010: Marine biodiversity, ecosystem functioning, and carbon cycles. *Proceedings of the National Academy of Sciences of the United States of America*, **107(22)**, 10120-10124.

Beaugrand, G., A. McQuatters-Gollop, M. Edwards, and E. Goberville, 2013: Long-term responses of North Atlantic calcifying plankton to climate change. *Nature Climate Change*, **3(3)**, 263-267.

Beaulieu, C., S.A. Henson, J.L. Sarmiento, J.P. Dunne, S.C. Doney, R.R. Rykaczewski, and L. Bopp, 2013: Factors challenging our ability to detect long-term trends in ocean chlorophyll. *Biogeosciences*, **10(4)**, 2711-2724.

Beaumont, N.J., M.C. Austen, J.P. Atkins, D. Burdon, S. Degraer, T.P. Dentinho, S. Derous, P. Holm, T. Horton, E. van Ierland, A.H. Marboe, D.J. Starkey, M. Townsend, and T. Zarzycki, 2007: Identification, definition and quantification of goods and services provided by marine biodiversity: implications for the ecosystem approach. *Marine Pollution Bulletin*, **54(3)**, 253-265.

Becker, B.H., M.Z. Peery, and S.R. Beissinger, 2007: Ocean climate and prey availability affect the trophic level and reproductive success of the marbled murrelet, an endangered seabird. *Marine Ecology Progress Series*, **329**, 267-279.

Bednaršek, N., G.A. Tarling, D.C.E. Bakker, S. Fielding, E.M. Jones, H.J. Venables, P. Ward, A. Kuzirian, B. Lézé, R.A. Feely, and E.J. Murphy, 2012: Extensive dissolution of live pteropods in the Southern Ocean. *Nature Geoscience*, **5(12)**, 881-885.

Behrenfeld, M., 2011: Uncertain future for ocean algae. *Nature Climate Change*, **1(1)**, 33-34.

Beman, J.M., C.-E. Chow, A.L. King, Y. Feng, J.A. Fuhrman, A. Andersson, N.R. Bates, B.N. Popp, and D.A. Hutchins, 2011: Global declines in oceanic nitrification rates as a consequence of ocean acidification. *Proceedings of the National Academy of Sciences of the United States of America*, **108(1)**, 208-213.

Beniash, E., A. Ivanina, N.S. Lieb, I. Kurochkin, and I.M. Sokolova, 2010: Elevated level of carbon dioxide affects metabolism and shell formation in oysters *Crassostrea virginica*. *Marine Ecology Progress Series*, **419**, 95-108.

Benson, S., P. Cook, J. Anderson, S. Bachu, H.B. Nimir, B. Basu, J. Bradshaw, G. Deguchi, J. Gale, G. von Goerne, W. Heidug, S. Holloway, R. Kamal, D. Keith, P. Lloyd, P. Rocha, B. Senior, J. Thomson, T. Torp, T. Wildenborg, M. Wilson, F. Zarlenga, and D. Zhou, 2005: Underground geological storage. In: *Carbon Dioxide Capture and Storage: A Special Report of IPCC Working Group III* [Metz, B., O. Davidson, H. de Corninck, M. Loos, and L. Meyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 195-276.

Bertrand, A., M. Ballón, and A. Chaigneau, 2010: Acoustic observation of living organisms reveals the upper limit of the oxygen minimum zone. *PLoS ONE*, **5(4)**, e10330, doi:10.1371/journal.pone.0010330.

Bertrand, E.M., M.A. Saito, J.M. Rose, C.R. Riesselman, M.C. Lohan, A.E. Noble, P.A. Lee, and G.R. DiTullio, 2007: Vitamin B-12 and iron colimitation of phytoplankton growth in the Ross Sea. *Limnology and Oceanography*, **52(3)**, 1079-1093.

Bianchi, D., E.D. Galbraith, D.A. Carozza, K.A.S. Mislan, and C.A. Stock, 2013: Intensification of open-ocean oxygen depletion by vertically migrating animals. *Nature Geoscience*, **6(7)**, 545-548.

Billé, R., R. Kelly, E. Harrould-Kolieb, D. Herr, F. Joos, K.J. Kroeker, D. Laffoley, A. Oschlies, and J.-P. Gattuso, 2013: Taking action against ocean acidification: a review of management and policy options. *Environmental Management*, **52**, 761-779.

Bissinger, J.E., D.J.S. Montagnes, J. Sharples, and D. Atkinson, 2008: Predicting marine phytoplankton maximum growth rates from temperature: improving on the Eppley curve using quantile regression. *Limnology and Oceanography*, **53(2)**, 487-493.

Blanchard, J.L., S. Jennings, R. Holmes, J. Harle, G. Merino, J.I. Allen, J. Holt, N.K. Dulvy, and M. Barange, 2012: Potential consequences of climate change for primary production and fish production in large marine ecosystems. *Philosophical Transactions of the Royal Society B*, **367(1605)**, 2979-2989.

Bode, A., J.A. Hare, W.K.W. Li, X.A.G. Morán, and L. Valdés, 2011: Chlorophyll and primary production in the North Atlantic. In: *ICES Cooperative Research Report No. 310* [Reid, P.C. and L. Valdés (eds.)]. International Council for the Exploration of the Sea, Copenhagen, Denmark, pp. 77-102.

Boetius, A., S. Albrecht, K. Bakker, C. Bienhold, J. Felden, M. Fernández-Méndez, S. Hendricks, C. Katlein, C. Lalande, T. Krumpen, M. Nicolaus, I. Peeken, B. Rabe, A. Rogacheva, E. Rybakova, R. Somavilla, F. Wenzhöfer, and the RV Polarstern ARK27-3-Shipboard Science Party, 2013: Export of algal biomass from the melting arctic sea ice. *Science*, **339(6126)**, 1430-1432.

Bolton, J.J. and K. Lüning, 1982: Optimal growth and maximal survival temperatures of Atlantic *Laminaria* species (Phaeophyta) in culture. *Marine Biology*, **66(1)**, 89-94.

Bopp, L., C. Le Quéré, M. Heimann, A.C. Manning, and P. Monfray, 2002: Climate-induced oceanic oxygen fluxes: implications for the contemporary carbon budget. *Global Biogeochemical Cycles*, **16(2)**, 1022, doi:10.1029/2001GB001445.

Bopp, L., L. Resplandy, J.D. Orr, S.C. Doney, J.P. Dunne, M. Gehlen, P. Halloran, C. Heinze, T. Ilyina, R. Séférian, J. Tijiputra, and M. Vichi, 2013: Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. *Biogeosciences*, **10(10)**, 6225-6245.

Bossdorf, O., C.L. Richards, and M. Pigliucci, 2008: Epigenetics for ecologists. *Ecology Letters*, **11(2)**, 106-115.

Botsford, L.W., M.D. Holland, J.F. Samhouri, J.W. White, and A. Hastings, 2011: Importance of age structure in models of the response of upper trophic levels to fishing and climate change. *ICES Journal of Marine Science*, **68(6)**, 1270-1283.

Bowler, C., A. Vardi, and A.E. Allen, 2010: Oceanographic and biogeochemical insights from diatom genomes. *Annual Review of Marine Science*, **2(1)**, 333-365.

Bown, P.R., J.A. Lees, and J.R. Young, 2004: Calcareous nannoplankton evolution and diversity through time. In: *Coccolithophores – From Molecular Processes to Global Impact* [Thierstein, H.R. and J.R. Young (eds.)]. Springer, Heidelberg, Germany, pp. 481-508.

Boyce, D.G., M.R. Lewis, and B. Worm, 2010: Global phytoplankton decline over the past century. *Nature*, **466(7306)**, 591-596.

Boyd, P.W., 2002: Environmental factors controlling phytoplankton processes in the Southern Ocean. *Journal of Phycology*, **38(5)**, 844-861.

Boyd, P.W., 2008: Ranking geo-engineering schemes. *Nature Geoscience*, **1(11)**, 722-724.

Boyd, P.W., 2011: Beyond ocean acidification. *Nature Geoscience*, **4(5)**, 273-274.

Boyd, P.W. and S.C. Doney, 2002: Modelling regional responses by marine pelagic ecosystems to global climate change. *Geophysical Research Letters*, **29(16)**, 53-1–53-4, doi:10.1029/2001GL014130.

Boyd, P.W. and D.A. Hutchins, 2012: Understanding the responses of ocean biota to a complex matrix of cumulative anthropogenic change. *Marine Ecology Progress Series*, **470**, 125-135.

Boyd, P.W., T. Jickells, C.S. Law, S. Blain, E.A. Boyle, K.O. Buesseler, K.H. Coale, J.J. Cullen, H.J. de Baar, M. Follows, M. Harvey, C. Lancelot, M. Levasseur, N.P. Owens, R. Pollard, R.B. Rivkin, J. Sarmiento, V. Schoemann, V. Smetacek, S. Takeda, A. Tsuda, S. Turner, and A.J. Watson, 2007: Mesoscale iron enrichment experiments 1993-2005: synthesis and future directions. *Science*, **315(5812)**, 612-617.

Boyd, P.W., R. Strzepek, F.X. Fu, and D.A. Hutchins, 2010: Environmental control of open-ocean phytoplankton groups: now and in the future. *Limnology and Oceanography*, **55(3)**, 1353-1376.

Boyd, P.W., C.S. Law, and S.C. Doney, 2011: A climate change atlas for the ocean. *Oceanography*, **24(2)**, 13-16.

Bradshaw, W.E. and C.M. Holzapfel, 2010: Light, time, and the physiology of biotic response to rapid climate change in animals. *Annual Review of Physiology*, **72(1)**, 147-166.

Brainard, R.E., C. Birkeland, C.M. Eakin, P. McElhany, M.W. Miller, M. Patterson, and G.A. Piniak, 2011: *Status Review Report of 82 Candidate Coral Species Petitioned under The U.S. Endangered Species Act*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA) Technical Memorandum, NOAA-TM-NMFS-PIFSC-27, Washington, DC, USA, 530 pp.

Bralower, T.J., 2002: Evidence of surface water oligotrophy during the Paleocene-Eocene thermal maximum: nannofossil assemblage data from Ocean Drilling Program Site 690, Maud Rise, Weddell Sea. *Paleoceanography*, **17(2)**, 1-15.

Branch, T.A., B.M. DeJoseph, L.J. Ray, and C.A. Wagner, 2013: Impacts of ocean acidification on marine seafood. *Trends in Ecology and Evolution*, **28(3)**, 178-186.

Brander, K., 2007: Global fish production and climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **104(50)**, 19709-19714.

Brander, K., 2008: Tackling the old familiar problems of pollution, habitat alteration and overfishing will help with adapting to climate change. *Marine Pollution Bulletin*, **56(12)**, 1957-1958.

Brander, K., G. Blom, M.F. Borges, K. Erzini, G. Henderson, B.R. MacKenzie, H. Mendes, J. Ribeiro, A.M.P. Santos, and R. Toresen, 2003: Changes in fish distribution in the eastern North Atlantic: are we seeing a coherent response to changing temperature? *ICES Marine Science Symposia*, **219**, 261-270.

Brander, L.M., K. Rehdanz, R.S.J. Tol, and P.J.H. Van Beukering, 2012: The economic impact of ocean acidification on coral reefs. *Climate Change Economics*, **3(1)**, 1250002, doi:10.1142/S2010007812500029.

Brandes, J.A., A.H. Devol, and C. Deutsch, 2007: New developments in the marine nitrogen cycle. *Chemical Reviews*, **107(2)**, 577-589.

Braun-McNeill, J., C.R. Sasso, S.P. Epperly, and C. Rivero, 2008: Feasibility of using sea surface temperature imagery to mitigate cheloniid sea turtle-fishery interactions off the coast of northeastern USA. *Endangered Species Research*, **5(2-3)**, 257-266.

Breau, C., R.A. Cunjak, and S.J. Peake, 2011: Behaviour during elevated water temperatures: can physiology explain movement of juvenile Atlantic salmon to cool water? *Journal of Animal Ecology*, **80(4)**, 844-853.

Brewer, P.G. and E.T. Peltzer, 2009: Limits to marine life. *Science*, **324(5925)**, 347-348.

Brinton, E. and A. Townsend, 2003: Decadal variability in abundances of the dominant euphausiid species in southern sectors of the California Current. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **50(14-16)**, 2449-2472.

Broderick, A.C., B.J. Godley, S. Reece, and J.R. Downie, 2000: Incubation periods and sex ratios of green turtles: highly female biased hatchling production in the eastern Mediterranean. *Marine Ecology Progress Series*, **202**, 273-281.

Brotz, L., W.W.L. Cheung, K. Kleisner, E. Pakhomov, and D. Pauly, 2012: Increasing jellyfish populations: trends in large marine ecosystems. *Hydrobiologia*, **690(1)**, 3-20.

Brown, C.J., E.A. Fulton, A.J. Hobday, R.J. Matear, H.P. Possingham, C. Bulman, V. Christensen, R.E. Forrest, P.C. Gehrke, N.A. Gribble, S.P. Griffiths, H. Lozano-Montes, J.M. Martin, S. Metcalf, T.A. Okey, R. Watson, and A.J. Richardson, 2010: Effects of climate-driven primary production change on marine food webs: implications for fisheries and conservation. *Global Change Biology*, **16(4)**, 1194-1212.

Brunel, T. and M. Dickey-Collas, 2010: Effects of temperature and population density on von Bertalanffy growth parameters in Atlantic herring: a macro-ecological analysis. *Marine Ecology Progress Series*, **405**, 15-28.

Bruno, J.F. and E.R. Selig, 2007: Regional decline of coral cover in the Indo-Pacific: timing, extent, and subregional comparisons. *PLoS ONE*, **2(8)**, e711, doi:10.1371/journal.pone.0000711.

Buesseler, K.O., S.C. Doney, D.M. Karl, P.W. Boyd, K. Caldeira, F. Chai, K.H. Coale, H.J. de Baar, P.G. Falkowski, K.S. Johnson, R.S. Lampitt, A.F. Michaels, S.W.A. Naqvi, V. Smetacek, S. Takeda, and A.J. Watson, 2008: Ocean iron fertilization – moving forward in a sea of uncertainty. *Science*, **319**, 162.

Bunce, A., F. Norman, N. Brothers, and R. Gales, 2002: Long-term trends in the Australasian gannet (*Morus serrator*) population in Australia: the effect of climate change and commercial fisheries. *Marine Biology*, **141(2)**, 263-269.

Burge, C.A., C.M. Eakin, C.S. Friedman, B. Froelich, P.K. Hershberger, E.E. Hofmann, L.E. Petes, K.C. Prager, E. Weil, B.L. Willis, S.E. Ford, and C.D. Harvell, 2014: Climate change influences on marine infectious diseases: implications for management and society. *Annual Review of Marine Science*, **6**, 249-277.

Burleson, M.L. and P.E. Silva, 2011: Cross tolerance to environmental stressors: effects of hypoxic acclimation on cardiovascular responses of channel catfish (*Ictalurus punctatus*) to a thermal challenge. *Journal of Thermal Biology*, **36(4)**, 250-254.

Burrows, M.T., D.S. Schoeman, L.B. Buckley, P. Moore, E.S. Poloczanska, K.M. Brander, C. Brown, J.F. Bruno, C.M. Duarte, B.S. Halpern, J. Holding, C.V. Kappel, W. Kiessling, M.I. O'Connor, J.M. Pandolfi, C. Parmesan, F.B. Schwing, W.J. Sydeman, and A.J. Richardson, 2011: The pace of shifting climate in marine and terrestrial ecosystems. *Science*, **334(6056)**, 652-655.

Cai, W.-J., X. Hu, W.-J. Huang, M.C. Murrell, J.C. Lehrter, S.E. Lohrenz, W.-C. Chou, W. Zhai, J.T. Hollibaugh, Y. Wang, P. Zhao, X. Guo, K. Gundersen, M. Dai, and G.-C. Gong, 2011: Acidification of subsurface coastal waters enhanced by eutrophication. *Nature Geoscience*, **4(11)**, 766-770.

Cairns, D.K., A.J. Gaston, and F. Huettmann, 2008: Endothermy, ectothermy and the global structure of marine vertebrate communities. *Marine Ecology Progress Series*, **356**, 239-250.

Calambokidis, J., J. Barlow, J.K.B. Ford, T.E. Chandler, and A.B. Douglas, 2009: Insights into the population structure of blue whales in the eastern North Pacific from recent sightings and photographic identification. *Marine Mammal Science*, **25(4)**, 816-832.

Caldeira, K. and L. Wood, 2008: Global and Arctic climate engineering: numerical model studies. *Philosophical Transactions of the Royal Society A*, **366(1882)**, 4039-4056.

Caldeira, K., M. Akai, P. Brewer, B. Chen, P. Haugan, T. Iwama, P. Johnston, H. Kheshgi, Q. Li, T. Ohsumi, H.-O. Pörtner, C. Sabine, Y. Shirayama, and J. Thomson, 2005: Ocean Storage. In: *Carbon Dioxide Capture and Storage: A Special Report of IPCC Working Group III* [Metz, B., O. Davidson, H.C. de Coninck, M. Loos, and L.A. Meyer (eds.)]. Cambridge University Press, Cambridge UK, pp. 277-318.

Calosi, P., S.P.S. Rastrick, M. Graziano, S.C. Thomas, C. Baggini, H.A. Carter, J.M. Hall-Spencer, M. Milazzo, and J.I. Spicer, 2013: Distribution of sea urchins living near shallow water CO_2 vents is dependent upon species acid–base and ion-regulatory abilities. *Marine Pollution Bulletin*, **73(2)**, 470-484.

Campbell, J., D. Antoine, R. Armstrong, K. Arrigo, W. Balch, R. Barber, M. Behrenfeld, R. Bidigare, J. Bishop, M.-E. Carr, W. Esaias, P. Falkowski, N. Hoepffner, R. Iverson, D. Kiefer, S. Lohrenz, J. Marra, A. Morel, J. Ryan, V. Vedernikov, K. Waters, C. Yentsch, and J. Yoder, 2002: Comparison of algorithms for estimating ocean primary production from surface chlorophyll, temperature, and irradiance. *Global Biogeochemical Cycles*, **16(3)**, 1035, doi:10.1029/2001GB001444.

Campbell, S.J., L.J. McKenzie, and S.P. Kerville, 2006: Photosynthetic responses of seven tropical seagrasses to elevated seawater temperature. *Journal of Experimental Marine Biology and Ecology*, **330(2)**, 455-468.

Cao, L. and K. Caldeira, 2010: Can ocean iron fertilization mitigate ocean acidification? *Climatic Change*, **99(1-2)**, 303-311.

Capotondi, A., M.A. Alexander, N.A. Bond, E.N. Curchitser, and J.D. Scott, 2012: Enhanced upper ocean stratification with climate change in the CMIP3 models. *Journal of Geophysical Research*, **117(C4)**, C04031, doi:10.1029/2011JC007409.

Carlton, J.T., 2000: Global change and biological invasions in the oceans. In: *Invasive Species in a Changing World* [Mooney, H.A. and R.J. Hobbs (eds.)]. Island Press, Covelo, CA, USA, pp. 31-53.

Carpenter, S.R. and W.A. Brock, 2006: Rising variance: a leading indicator of ecological transition. *Ecology Letters*, **9(3)**, 311-318.

Carrillo, C.J., R.C. Smith, and D.M. Karl, 2004: Processes regulating oxygen and carbon dioxide in surface waters west of the Antarctic Peninsula. *Marine Chemistry*, **84(3-4)**, 161-179.

Casini, M., J. Hjelm, J.C. Molinero, J. Lövgren, M. Cardinale, V. Bartolino, A. Belgrano, and G. Kornilovs, 2009: Trophic cascades promote threshold-like shifts in pelagic marine ecosystems. *Proceedings of the National Academy of Sciences of the United States of America*, **106(1)**, 197-202.

Cavalier-Smith, T., 2004: Only six kingdoms of life. *Proceedings of the Royal Society B: Biological Sciences*, **271(1545)**, 1251-1262.

CBD, 2009: *Scientific Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity.* Secretariat of the Convention on Biological Diversity (CBD) Technical Series No. 46, CBD, Montreal, Canada, 61 pp.

Cesar, H., L. Burke, and L. Pet-Soede, 2003: *The Economics of Worldwide Coral Reef Degradation*. Cesar Environmental Economics Consulting (CEEC), Arnhem, Netherlands, 23 pp.

Chaloupka, M., N. Kamezaki, and C. Limpus, 2008: Is climate change affecting the population dynamics of the endangered Pacific loggerhead sea turtle? *Journal of Experimental Marine Biology and Ecology*, **356(1-2)**, 136-143.

Chambers, L.E., L. Hughes, and M.A. Weston, 2005: Climate change and its impact on Australia's avifauna. *Emu*, **105(1)**, 1-20.

Chambers, L.E., C.A. Devney, B.C. Congdon, N. Dunlop, E.J. Woehler, and P. Dann, 2011: Observed and predicted effects of climate on Australian seabirds. *Emu*, **111(3)**, 235-251.

Chan, F., J.A. Barth, J. Lubchenco, A. Kirincich, H. Weeks, W.T. Peterson, and B.A. Menge, 2008: Emergence of anoxia in the California Current large marine ecosystem. *Science*, **319(5865)**, 920.

Charpy-Roubaud, C. and A. Sournia, 1990: The comparative estimation of phytoplanktonic, microphytobenthic and macrophytobenthic primary production in the oceans. *Marine Microbial Food Webs*, **4(1)**, 31-57.

Chavez, F.P., J. Ryan, S.E. Lluch-Cota, and M. Niquen C, 2003: From anchovies to sardines and back: multidecadal change in the Pacific Ocean. *Science*, **299(5604)**, 217-221.

Chavez, F.P., M. Messié, and J.T. Pennington, 2011: Marine primary production in relation to climate variability and change. *Annual Review of Marine Science*, **3(1)**, 227-260.

Checkley Jr., D.M., A.G. Dickson, M. Takahashi, J.A. Radich, N. Eisenkolb, and R. Asch, 2009: Elevated CO_2 enhances otolith growth in young fish. *Science*, **324(5935)**, 1683.

Cheung, W.W.L., C. Close, V. Lam, R. Watson, and D. Pauly, 2008: Application of macroecological theory to predict effects of climate change on global fisheries potential. *Marine Ecology Progress Series*, **365**, 187-197.

Cheung, W.W.L., V.W.Y. Lam, J.L. Sarmiento, K. Kearney, R. Watson, and D. Pauly, 2009: Projecting global marine biodiversity impacts under climate change scenarios. *Fish and Fisheries*, **10(3)**, 235-251.

Cheung, W.W.L., V.W.Y. Lam, J.L. Sarmiento, K. Kearney, R. Watson, D. Zeller, and D. Pauly, 2010: Large-scale redistribution of maximum fisheries catch in the global ocean under climate change. *Global Change Biology*, **16(1)**, 24-35.

Cheung, W.W.L., J. Dunne, J.L. Sarmiento, and D. Pauly, 2011: Integrating ecophysiology and plankton dynamics into projected maximum fisheries catch potential under climate change in the Northeast Atlantic. *ICES Journal of Marine Science*, **68(6)**, 1008-1018.

Cheung, W.W.L., R. Watson, and D. Pauly, 2013a: Signature of ocean warming in global fisheries catch. *Nature*, **497**, 365-368.

Cheung, W.W.L., J.L. Sarmiento, J. Dunne, T.L. Frölicher, V.W.Y. Lam, M.L.D. Palomares, R. Watson, and D. Pauly, 2013b: Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. *Nature Climate Change*, **3(3)**, 254-258.

Chevaldonné, P., C. Fisher, J. Childress, D. Desbruyères, D. Jollivet, F. Zal, and A. Toulmond, 2000: Thermotolerance and the 'Pompeii worms'. *Marine Ecology Progess Series*, **208**, 2093-2295.

Chevin, L.-M., R. Lande, and G.M. Mace, 2010: Adaptation, plasticity, and extinction in a changing environment: towards a predictive theory. *PLoS Biology*, **8(4)**, e1000357, doi:10.1371/journal.pbio.1000357.

Christen, N., P. Calosi, C.L. McNeill, and S. Widdicombe, 2013: Structural and functional vulnerability to elevated pCO_2 in marine benthic communities. *Marine Biology*, **160**, 2113-2128.

Christian, J.R. and D.M. Karl, 1995: Bacterial ectoenzymes in marine waters – activity ratios and temperature responses in 3 oceanographic provinces. *Limnology and Oceanography*, **40(6)**, 1042-1049.

Claiborne, J.B., S.L. Edwards, and A.I. Morrison-Shetlar, 2002: Acid–base regulation in fishes: cellular and molecular mechanisms. *Journal of Experimental Zoology*, **293(3)**, 302-319.

Clark, D., M. Lamare, and M. Barker, 2009: Response of sea urchin pluteus larvae (Echinodermata: Echinoidea) to reduced seawater pH: a comparison among a tropical, temperate, and a polar species. *Marine Biology*, **156(6)**, 1125-1137.

CLIMAP Project Members, 1976: The surface of the ice-age earth. *Science*, **191(4232)**, 1131-1137.

Colbourne, E., J. Craig, C. Fitzpatrick, D. Senciall, P. Stead, and W. Bailey, 2011: *An Assessment of the Physical Oceanographic Environment on the Newfoundland and Labrador Shelf during 2010*. Department of Fisheries and Oceans (DFO), Canadian Science Advisory Secretariat (CSAS) Science Advisory Report 2011/089, CSAS, Ottawa, Ontario, Canada, 31 pp.

Coll, M., L.J. Shannon, D. Yemane, J.S. Link, H. Ojaveer, S. Neira, D. Jouffre, P. Labrosse, J.J. Heymans, E.A. Fulton, and Y.-J. Shin, 2010: Ranking the ecological relative status of exploited marine ecosystems. *ICES Journal of Marine Science*, **67(4)**, 769-786.

Comeau, A.M., W.K.W. Li, J.E. Tremblay, E.C. Carmack, and C. Lovejoy, 2011: Arctic ocean microbial community structure before and after the 2007 record sea ice minimum. *PLoS ONE*, **6(11)**, e27492, doi:10.1371/journal.pone.0027492.

Comeau, S., G. Gorsky, R. Jeffree, J.L. Teyssié, and J.-P. Gattuso, 2009: Impact of ocean acidification on a key Arctic pelagic mollusc (*Limacina helicina*). *Biogeosciences*, **6(9)**, 1877-1882.

Condon, R.H., W.M. Graham, C.M. Duarte, K.A. Pitt, C.H. Lucas, S.H.D. Haddock, K.R. Sutherland, K.L. Robinson, M.N. Dawson, M.B. Decker, C.E. Mills, J.E. Purcell, A. Malej, H. Mianzan, S.-I. Uye, S. Gelcich, and L.P. Madin, 2012: Questioning the rise of gelatinous zooplankton in the world's oceans. *BioScience*, **62(2)**, 160-169.

Condon, R.H., C.M. Duarte, K.A. Pitt, K.L. Robinson, C.H. Lucas, K.R. Sutherland, H.W. Mianzan, M. Bogeberg, J.E. Purcell, M.B. Decker, S. Uye, L.P. Madin, R.D. Brodeur, S.H.D. Haddock, A. Malej, G.D. Parry, E. Eriksen, J. Quiñones, M. Acha, M. Harvey, J.M. Arthur, and W.M. Graham, 2013: Recurrent jellyfish blooms are a

consequence of global oscillations. *Proceedings of the National Academy of Sciences of the United States of America*, **110(3)**, 1000-1005.

Cooley, S.R., 2012: How humans could "feel" changing biogeochemistry. *Current Opinion in Environmental Sustainability*, **4(3)**, 258-263.

Cooley, S.R. and S.C. Doney, 2009: Anticipating ocean acidification's economic consequences for commercial fisheries. *Environmental Research Letters*, **4(2)**, 024007, doi:10.1088/1748-9326/4/2/024007.

Cooley, S.R., H.L. Kite-Powell, and S.C. Doney, 2009: Ocean acidification's potential to alter global marine ecosystem services. *Oceanography*, **22(4)**, 172-181.

Cooley, S.R., N. Lucey, H. Kite-Powell, and S.C. Doney, 2012: Nutrition and income from molluscs today imply vulnerability to ocean acidification tomorrow. *Fish and Fisheries*, **13(2)**, 182-215.

Corbett, J.J., D.A. Lack, J.J. Winebrake, S. Harder, J.A. Silberman, and M. Gold, 2010: Arctic shipping emissions inventories and future scenarios. *Atmospheric Chemistry and Physics*, **10(19)**, 9689-9704.

Costello, J.H., B.K. Sullivan, and D.J. Gifford, 2006: A physical-biological interaction underlying variable phenological responses to climate change by coastal zooplankton. *Journal of Plankton Research*, **28(11)**, 1099-1105.

Crain, C.M., K. Kroeker, and B.S. Halpern, 2008: Interactive and cumulative effects of multiple human stressors in marine systems. *Ecology Letters*, **11(12)**, 1304-1315.

Crook, E.D., D. Potts, M. Rebolledo-Vieyra, L. Hernandez, and A. Paytan, 2012: Calcifying coral abundance near low-pH springs: implications for future ocean acidification. *Coral Reefs*, **31(1)**, 239-245.

Crutzen, P., 2006: Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma? *Climatic Change*, **77(3-4)**, 211-220.

Cubillos, J.C., S.W. Wright, G. Nash, M.F. de Salas, B. Griffiths, B. Tilbrook, A. Poisson, and G.M. Hallegraeff, 2007: Calcification morphotypes of the coccolithophorid *Emiliania huxleyi* in the Southern Ocean: changes in 2001 to 2006 compared to historical data. *Marine Ecology Progress Series*, **348**, 47-54.

Cuevas, E., F.A. Abreu-Grobois, V. Guzmán-Hernández, M.A. Liceaga-Correa, and R.P. van Dam, 2008: Post-nesting migratory movements of hawksbill turtles *Eretmochelys imbricata* in waters adjacent to the Yucatan Peninsula, Mexico. *Endangered Species Research*, **10**, 123-133.

Cui, Y., L.R. Kump, A.J. Ridgwell, A.J. Charles, C.K. Junium, A.F. Diefendorf, K.H. Freeman, N.M. Urban, and I.C. Harding, 2011: Slow release of fossil carbon during the Palaeocene-Eocene Thermal Maximum. *Nature Geoscience*, **4(7)**, 481-485.

Cury, P., L. Shannon, and Y.-J. Shin, 2003: The functioning of marine ecosystems: a fisheries perspective. In: *Responsible Fisheries in the Marine Ecosystem* [Sinclair, M. and G. Valdimarsson (eds.)]. Food and Agriculture Organization of the United Nations (FAO) and CABI Publishing, Wallingford, UK, pp. 103-124.

Czerny, J., J. Barcelos e Ramos, and U. Riebesell, 2009: Influence of elevated CO_2 concentrations on cell division and nitrogen fixation rates in the bloom-forming cyanobacterium *Nodularia spumigena*. *Biogeosciences*, **6(9)**, 1865-1875.

Dale, B., M. Edwards, and P.C. Reid, 2006: Climate change and harmful algal blooms. In: *Ecology of Harmful Algae* [Granéli, E. and J.T. Turner (eds.)]. Springer, Berlin, Germany, pp. 367-378.

Danovaro, R., C. Corinaldesi, A. Dell'Anno, J.A. Fuhrman, J.J. Middelburg, R.T. Noble, and C.A. Suttle, 2011: Marine viruses and global climate change. *FEMS Microbiology Reviews*, **35(6)**, 993-1034.

Daskalov, G.M., 2003: Long-term changes in fish abundance and environmental indices in the Black Sea. *Marine Ecology Progress Series*, **255**, 259-270.

Daufresne, M., K. Lengfellner, and U. Sommer, 2009: Global warming benefits the small in aquatic ecosystems. *Proceedings of the National Academy of Sciences of the United States of America*, **106(31)**, 12788-12793.

de Baar, H.J.W., J.T.M. de Jong, D.C.E. Bakker, B.M. Löscher, C. Veth, U. Bathmann, and V. Smetacek, 1995: Importance of iron for plankton blooms and carbon dioxide drawdown in the Southern Ocean. *Nature*, **373**, 412-415.

de Baar, H.J.W., P.W. Boyd, K.H. Coale, M.R. Landry, A. Tsuda, P. Assmy, D.C.E. Bakker, Y. Bozec, R.T. Barber, M.A. Brzezinski, K.O. Buesseler, M. Boyé, P.L. Croot, F. Gervais, M.Y. Gorbunov, P.J. Harrison, W.T. Hiscock, P. Laan, C. Lancelot, C.S. Law, M. Levasseur, A. Marchetti, F.J. Millero, J. Nishioka, Y. Nojiri, T. van Oijen, U. Riebesell, M.J.A. Rijkenberg, H. Saito, S. Takeda, K.R. Timmermans, M.J.W. Veldhuis, A.M. Waite, and C.-S. Wong, 2005: Synthesis of iron fertilization experiments: from the Iron Age in the Age of Enlightenment. *Journal of Geophysical Research*, **110(C9)**, C09S16, doi:10.1029/2004JC002601.

De Jonckheere, J.F., M. Baumgartner, F.R. Opperdoes, and K.O. Stetter, 2009: *Marinamoeba thermophila,* a new marine heterolobosean amoeba growing at 50°C. *European Journal of Protistology*, **45(3)**, 231-236.

De Jonckheere, J.F., M. Baumgartner, S. Eberhardt, F.R. Opperdoes, and K.O. Stetter, 2011: *Oramoeba fumarolia* gen. nov., sp. nov., a new marine heterolobosean amoeboflagellate growing at 54°C. *European Journal of Protistology*, **47(1)**, 16-23.

de Moel, H., G.M. Ganssen, F.J.C. Peeters, S.J.A. Jung, D. Kroon, G.J.A. Brummer, and R.E. Zeebe, 2009: Planktic foraminiferal shell thinning in the Arabian Sea due to anthropogenic ocean acidification? *Biogeosciences*, **6(9)**, 1917-1925.

De'ath, G., J.M. Lough, and K.E. Fabricius, 2009: Declining coral calcification on the Great Barrier Reef. *Science*, **323(5910)**, 116-119.

De'ath, G., K.E. Fabricius, H. Sweatman, and M. Puotinen, 2012: The 27-year decline of coral cover on the Great Barrier Reef and its causes. *Proceedings of the National Academy of Sciences of the United States of America*, **109(44)**, 17995-17999.

De'ath, G., J.M. Lough, and K.E. Fabricius, 2013: Corrigendum: declining coral calcification on the Great Barrier Reef. *Science*, **342(6158)**, 559.

Deigweiher, K., N. Koschnick, H.-O. Pörtner, and M. Lucassen, 2008: Acclimation of ion regulatory capacities in gills of marine fish under environmental hypercapnia. *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology*, **295(5)**, R1660-1670.

Denman, K., J.R. Christian, N. Steiner, H.-O. Pörtner, and Y. Nojiri, 2011: Potential impacts of future ocean acidification on marine ecosystems and fisheries: present knowledge and recommendations for future research. *ICES Journal of Marine Science*, **68(6)**, 1019-1029.

Deutsch, C., H. Brix, T. Ito, H. Frenzel, and L. Thompson, 2011: Climate-forced variability of ocean hypoxia. *Science*, **333(6040)**, 336-339.

deYoung, B., R. Harris, J. Alheit, G. Beaugrand, N. Mantua, and L. Shannon, 2004: Detecting regime shifts in the ocean: data considerations. *Progress in Oceanography*, **60(2-4)**, 143-164.

deYoung, B., M. Barange, G. Beaugrand, R. Harris, R.I. Perry, M. Scheffer, and F. Werner, 2008: Regime shifts in marine ecosystems: detection, prediction and management. *Trends in Ecology and Evolution*, **23(7)**, 402-409.

DFO, 2011a: *Assessment of Capelin in SA 2 + Div. 3KL in 2010*. Department of Fisheries and Oceans (DFO), Canadian Science Advisory Secretariat (CSAS) Science Advisory Report 2010/090, CSAS, Ottawa, Ontario, Canada, 16 pp.

DFO, 2011b: *Recovery potential assessment for the Newfoundland and Labrador designatable unit (NAFO Divs. 2GHJ, 3KLNO) of Atlantic Cod (Gadus morhua)*. Department of Fisheries and Oceans (DFO), Canadian Science Advisory Secretariat (CSAS) Science Advisory Report 2011/037, CSAS, Ottawa, Ontario, Canada, 30 pp.

Díaz, R.J. and R. Rosenberg, 2008: Spreading dead zones and consequences for marine ecosystems. *Science*, **321(5891)**, 926-929.

Dierssen, H.M., 2010: Perspectives on empirical approaches for ocean color remote sensing of chlorophyll in a changing climate. *Proceedings of the National Academy of Sciences of the United States of America*, **107(40)**, 17073-17078.

Doak, D.F., J.A. Estes, B.S. Halpern, U. Jacob, D.R. Lindberg, J. Lovvorn, D.H. Monson, M.T. Tinker, T.M. Williams, J.T. Wootton, I. Carroll, M. Emmerson, F. Micheli, and M. Novak, 2008: Understanding and predicting ecological dynamics: are major surprises inevitable? *Ecology*, **89(4)**, 952-961.

Dobson, A., 2009: Climate variability, global change, immunity, and the dynamics of infectious diseases. *Ecology*, **90(4)**, 920-927.

Dodds, L.A., J.M. Roberts, A.C. Taylor, and F. Marubini, 2007: Metabolic tolerance of the cold-water coral *Lophelia pertusa* (Scleractinia) to temperature and dissolved oxygen change. *Journal of Experimental Marine Biology and Ecology*, **349(2)**, 205-214.

Dodson, J.J., S. Tremblay, F. Colombani, J.E. Carscadden, and F. Lecomte, 2007: Trans-Arctic dispersals and the evolution of a circumpolar marine fish species complex, the capelin (*Mallotus villosus*). *Molecular Ecology*, **16(23)**, 5030-5043.

Domenici, P., B. Allan, M.I. McCormick, and P.L. Munday, 2012: Elevated carbon dioxide affects behavioural lateralization in a coral reef fish. *Biology Letters*, **8(1)**, 78-81.

Donelson, J.M., P.L. Munday, M.I. McCormick, and C.R. Pitcher, 2012: Rapid transgenerational acclimation of a tropical reef fish to climate change. *Nature Climate Change*, **2(1)**, 30-32.

Doney, S.C., 2006: Oceanography: plankton in a warmer world. *Nature*, **444(7120)**, 695-696.

Doney, S.C., 2010: The growing human footprint on coastal and open-ocean biogeochemistry. *Science*, **328(5985)**, 1512-1516.

Donner, S.D., W.J. Skirving, C.M. Little, M. Oppenheimer, and O. Hoegh-Guldberg, 2005: Global assessment of coral bleaching and required rates of adaptation under climate change. *Global Change Biology*, **11(12)**, 2251-2265.

Dore, J.E., R. Lukas, D.W. Sadler, M.J. Church, and D.M. Karl, 2009: Physical and biogeochemical modulation of ocean acidification in the central North Pacific. *Proceedings of the National Academy of Sciences of the United States of America*, **106(30)**, 12235-12240.

Douvere, F., 2008: The importance of marine spatial planning in advancing ecosystem-based sea use management. *Marine Policy*, **32(5)**, 762-771.

Dove, S.G., D.I. Kline, O. Pantos, F.E. Angly, G.W. Tyson, and O. Hoegh-Guldberg, 2013: Future reef decalcification under a business-as-usual CO_2 emission scenario. *Proceedings of the National Academy of Sciences of the United States of America*, **110(38)**, 15342-15347.

Dowsett, H.J., 2007: The PRISM palaeoclimate reconstruction and Pliocene sea-surface temperature. In: *Deep-time Perspectives on Climate Change: Marrying the Signal from Computer Models and Biological Proxies* [Williams, M., A.M. Haywood, F.J. Gregory, and D.N. Schmidt (eds.)]. The Micropalaeontological Society Special Publication, The Geological Society, London, UK, pp. 459-480.

Drinkwater, K.F., 2006: The regime shift of the 1920s and 1930s in the North Atlantic. *Progress in Oceanography*, **68(2-4)**, 134-151.

Drinkwater, K.F., G. Beaugrand, M. Kaeriyama, S. Kim, G. Ottersen, R.I. Perry, H.-O. Pörtner, J.J. Polovina, and A. Takasuka, 2010: On the processes linking climate to ecosystem changes. *Journal of Marine Systems*, **79(3-4)**, 374-388.

Duce, R.A., J. LaRoche, K. Altieri, K.R. Arrigo, A.R. Baker, D.G. Capone, S. Cornell, F. Dentener, J. Galloway, R.S. Ganeshram, R.J. Geider, T. Jickells, M.M. Kuypers, R. Langlois, P.S. Liss, S.M. Liu, J.J. Middelburg, C.M. Moore, S. Nickovic, A. Oschlies, T. Pedersen, J. Prospero, R. Schlitzer, S. Seitzinger, L.L. Sorensen, M. Uematsu, O. Ulloa, M. Voss, B. Ward, and L. Zamora, 2008: Impacts of atmospheric anthropogenic nitrogen on the open ocean. *Science*, **320(5878)**, 893-897.

Dulvy, N.K., S.I. Rogers, S. Jennings, V. Stelzenmüller, S.R. Dye, and H.R. Skjoldal, 2008: Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. *Journal of Applied Ecology*, **45(4)**, 1029-1039.

Dunkley Jones, T., D.J. Lunt, D.N. Schmidt, A. Ridgwell, A. Sluijs, P.J. Valdes, and M. Maslin, 2013: Climate model and proxy data constraints on ocean warming across the Paleocene–Eocene Thermal Maximum. *Earth-Science Reviews*, **125**, 123-145.

Dunne, J.A. and R.J. Williams, 2009: Cascading extinctions and community collapse in model food webs. *Philosophical Transactions of the Royal Society B*, **364(1524)**, 1711-1723.

Dupont, S., B. Lundve, and M. Thorndyke, 2010: Near future ocean acidification increases growth rate of the lecithotrophic larvae and juveniles of the sea star *Crossaster papposus*. *Journal of Experimental Zoology Part B: Molecular and Developmental Evolution*, **314(5)**, 382-389.

Dupont, S., N. Dorey, M. Stumpp, F. Melzner, and M. Thorndyke, 2013: Long-term and trans-life-cycle effects of exposure to ocean acidification in the green sea urchin *Strongylocentrotus droebachiensis*. *Marine Biology*, **160(8)**, 1835-1843.

Durack, P.J., S.E. Wijffels, and R.J. Matear, 2012: Ocean salinities reveal strong global water cycle intensification during 1950 to 2000. *Science*, **336(6080)**, 455-458.

Dyhrman, S.T., S.T. Haley, S.R. Birkeland, L.L. Wurch, M.J. Cipriano, and A.G. McArthur, 2006: Long serial analysis of gene expression for gene discovery and transcriptome profiling in the widespread marine coccolithophore *Emiliania huxleyi*. *Applied and Environmental Microbiology*, **72(1)**, 252-260.

Easterling, D.R., G.A. Meehl, C. Parmesan, S.A. Changnon, T.R. Karl, and L.O. Mearns, 2000: Climate extremes: observations, modeling, and impacts. *Science*, **289(5487)**, 2068-2074.

Edmunds, P.J., 2011: Zooplanktivory ameliorates the effects of ocean acidification on the reef coral *Porites* spp. *Limnology and Oceanography*, **56(6)**, 2402-2410.

Edwards, M. and A.J. Richardson, 2004: Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature*, **430(7002)**, 881-884.

Edwards, M., P.C. Reid, and B. Planque, 2001: Long-term and regional variability of phytoplankton biomass in the Northeast Atlantic (1960-1995). *ICES Journal of Marine Science*, **58(1)**, 39-49.

Edwards, M., D.G. Johns, S.C. Leterme, E. Svendsen, and A.J. Richardson, 2006: Regional climate change and harmful algal blooms in the Northeast Atlantic. *Limnology and Oceanography*, **51(2)**, 820-829.

Edwards, M., G. Beaugrand, P. Helaouët, J. Alheit, and S. Coombs, 2013: Marine ecosystem response to the Atlantic Multidecadal Oscillation. *PLoS ONE*, **8(2)**, e57212, doi:10.1371/journal.pone.0057212.

Eero, M., B.R. MacKenzie, F.W. Koster, and H. Gislason, 2011: Multi-decadal responses of a cod (*Gadus morhua*) population to human-induced trophic changes, fishing, and climate. *Ecological Applications*, **21(1)**, 214-226.

Eggert, A., R.J.W. Visser, P.R. Van Hasselt, and A.M. Breeman, 2006: Differences in acclimation potential of photosynthesis in seven isolates of the tropical to warm temperate macrophyte *Valonia utricularis* (Chlorophyta). *Phycologia*, **45(5)**, 546-556.

Eide, A., 2007: Economic impacts of global warming: the case of the Barents Sea fisheries. *Natural Resource Modeling*, **20(2)**, 199-221.

Eide, A. and K. Heen, 2002: Economic impacts of global warming:a study of the fishing industry in North Norway. *Fisheries Research*, **56(3)**, 261-274.

Ekau, W., H. Auel, H.-O. Pörtner, and D. Gilbert, 2010: Impacts of hypoxia on the structure and processes in pelagic communities (zooplankton, macro-invertebrates and fish). *Biogeosciences*, **7(5)**, 1669-1699.

Eliason, E.J., T.D. Clark, M.J. Hague, L.M. Hanson, Z.S. Gallagher, K.M. Jeffries, M.K. Gale, D.A. Patterson, S.G. Hinch, and A.P. Farrell, 2011: Differences in thermal tolerance among sockeye salmon populations. *Science*, **332(6025)**, 109-112.

Elmqvist, T., C. Folke, M. Nyström, G. Peterson, J. Bengtsson, B. Walker, and J. Norberg, 2003: Response diversity, ecosystem change, and resilience. *Frontiers in Ecology and the Environment*, **1(9)**, 488-494.

Enfield, D.B., A.M. Mestas-Nuñez, and P.J. Trimble, 2001: The Atlantic Multidecadal Oscillation and its relation to rainfall and river flows in the continental U.S. *Geophysical Research Letters*, **28(10)**, 2077-2080.

Engel, A., S. Thoms, U. Riebesell, E. Rochelle-Newall, and I. Zondervan, 2004: Polysaccharide aggregation as a potential sink of marine dissolved organic carbon. *Nature*, **428(6986)**, 929-932.

Eppley, R.W., 1972: Temperature and phytoplankton growth in the sea. *Fishery Bulletin*, **70(4)**, 1063-1085.

Etheridge, D.M., L.P. Steele, R.L. Langenfelds, R.J. Francey, J.M. Barnola, and V.I. Morgan, 1996: Natural and anthropogenic changes in atmospheric CO_2 over the last 1000 years from air in Antarctic ice and firn. *Journal of Geophysical Research*, **101(D2)**, 4115-4128.

Fabricius, K.E., C. Langdon, S. Uthicke, C. Humphrey, S. Noonan, G. De'ath, R. Okazaki, N. Muehllehner, M.S. Glas, and J.M. Lough, 2011: Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations. *Nature Climate Change*, **1(3)**, 165-169.

Fairweather, T.P., C.D. van der Lingen, A.J. Booth, L. Drapeau, and J.J. van der Westhuizen, 2006: Indicators of sustainable fishing for South African sardine *Sardinops sagax* and anchovy *Engraulis encrasicolus*. *African Journal of Marine Science*, **28(3-4)**, 661-680.

Falkenberg, L.J., S.D. Connell, and B.D. Russell, 2013: Disrupting the effects of synergies between stressors: improved water quality dampens the effects of future CO_2 on a marine habitat. *Journal of Applied Ecology*, **50(1)**, 51-58.

Falkowski, P.G., 1997: Evolution of the nitrogen cycle and its influence on the biological sequestration of CO_2 in the ocean. *Nature*, **387(6630)**, 272-275.

Falkowski, P.G. and J.A. Raven, 1997: *Aquatic Photosynthesis*. Blackwell Science, Oxford, UK, 375 pp.

FAO, 2003: *The Ecosystem Approach to Fisheries*. FAO Technical Guidelines for Responsible Fisheries, No. 4, Suppl. 2, Food and Agricultural Organization of the United Nations (FAO), Rome, Italy, 112 pp.

FAO, 2012a: PART 3 – Feeding the world. Trends in the livestock sector. In: *FAO Statistical Yearbook 2012. World Food and Agriculture* [Prakash, A. and M. Stigler (eds.)]. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, pp. 198-213.

FAO, 2012b: *The State of World Fisheries and Aquaculture 2012*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 209 pp.

Fashchuk, D.Y., 2011: *Marine Ecological Geography. Theory and Experience*. Springer, Berlin, Germany, 433 pp.

Feely, R.A., C.L. Sabine, J.M. Hernandez-Ayon, D. Ianson, and B. Hales, 2008: Evidence for upwelling of corrosive "acidified" water onto the continental shelf. *Science*, **320(5882)**, 1490-1492.

Feely, R.A., S.R. Alin, J. Newton, C.L. Sabine, M. Warner, A. Devol, C. Krembs, and C. Maloy, 2010: The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary. *Estuarine, Coastal and Shelf Science*, **88(4)**, 442-449.

Feng, Y., C.E. Hare, K. Leblanc, J.M. Rose, Y. Zhang, G.R. DiTullio, P.A. Lee, S.W. Wilhelm, J.M. Rowe, J. Sun, N. Nemcek, C. Gueguen, U. Passow, I. Benner, C. Brown, and D.A. Hutchins, 2009: Effects of increased pCO_2 and temperature on the North Atlantic spring bloom. I. The phytoplankton community and biogeochemical response. *Marine Ecology Progress Series*, **388**, 13-25.

Fernandez, C., L. Farías, and O. Ulloa, 2011: Nitrogen fixation in denitrified marine waters. *PLoS ONE*, **6(6)**, e20539, doi:10.1371/journal.pone.0020539.

Fernández-Reiriz, M.J., P. Range, X.A. Álvarez-Salgado, and U. Labarta, 2011: Physiological energetics of juvenile clams (*Ruditapes decussatus*) in a high CO_2 coastal ocean. *Marine Ecology Progress Series*, **433**, 97-105.

Fernando, H.J.S., J.L. McCulley, S.G. Mendis, and K. Perera, 2005: Coral poaching worsens Tsunami destruction in Sri Lanka. *Eos Transactions of the American Geophysical Union*, **86(33)**, 301-304.

Ferrari, M.C.O., D.L. Dixson, P.L. Munday, M.I. McCormick, M.G. Meekan, A. Sih, and D.P. Chivers, 2011: Intrageneric variation in antipredator responses of coral reef fishes affected by ocean acidification: implications for climate change projections on marine communities. *Global Change Biology*, **17(9)**, 2980-2986.

Field, C.B., M.J. Behrenfeld, J.T. Randerson, and P. Falkowski, 1998: Primary production of the biosphere: integrating terrestrial and oceanic components. *Science*, **281(5374)**, 237-240.

Field, D.B., T.R. Baumgartner, C.D. Charles, V. Ferreira-Bartrina, and M.D. Ohman, 2006: Planktonic foraminifera of the California Current reflect 20th-century warming. *Science*, **311(5757)**, 63-66.

Findlay, H.S., M.A. Kendall, J.I. Spicer, and S. Widdicombe, 2010: Post-larval development of two intertidal barnacles at elevated CO_2 and temperature. *Marine Biology*, **157(4)**, 725-735.

Fish, M.R., A. Lombana, and C. Drews, 2009: *Climate Change and Marine Turtles in the Wider Caribbean: Regional Climate Projections*. World Wildlife Federation (WWF) Report, San José, Costa Rica, 18 pp.

Flombaum, P., J.L. Gallegos, R.A. Gordillo, J. Rincón, L.L. Zabala, N. Jiao, D.M. Karl, W.K.W. Li, M.W. Lomas, D. Veneziano, C.S. Vera, J.A. Vrugt, and A.C. Martiny, 2013: Present and future global distributions of the marine Cyanobacteria *Prochlorococcus* and *Synechococcus*. *Proceedings of the National Academy of Sciences of the United States of America*, **110(24)**, 9824-9829.

Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, and C.S. Holling, 2004: Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Review of Ecology, Evolution, and Systematics*, **35(1)**, 557-581.

Folt, C.L., C.Y. Chen, M.V. Moore, and J. Burnaford, 1999: Synergism and antagonism among multiple stressors. *Limnology and Oceanography*, **44(3)**, 864-877.

Form, A. and U. Riebesell, 2012: Acclimation to ocean acidification during long-term CO_2 exposure in the cold-water coral *Lophelia pertusa*. *Global Change Biology*, **18(3)**, 843-853.

Foster, L.C., D.N. Schmidt, E. Thomas, S. Arndt, and A. Ridgwell, 2013: Surviving rapid climate change in the deep sea during the Paleogene hyperthermals. *Proceedings of the National Academy of Sciences of the United States of America*, **110(23)**, 9273-9276.

Frank, K.T., B. Petrie, J.S. Choi, and W.C. Leggett, 2005: Trophic cascades in a formerly cod-dominated ecosystem. *Science*, **308(5728)**, 1621-1623.

Franz, J., G. Krahmann, G. Lavik, P. Grasse, T. Dittmar, and U. Riebesell, 2012: Dynamics and stoichiometry of nutrients and phytoplankton in waters influenced by the oxygen minimum zone in the eastern tropical Pacific. *Deep-Sea Research Part I: Oceanographic Research Papers*, **62**, 20-31.

Friedland, K.D. and C.D. Todd, 2012: Changes in Northwest Atlantic Arctic and Subarctic conditions and the growth response of Atlantic salmon. *Polar Biology*, **35(4)**, 593-609.

Friedland, K.D., C. Stock, K.F. Drinkwater, J.S. Link, R.T. Leaf, B.V. Shank, J.M. Rose, C.H. Pilskaln, and M.J. Fogarty, 2012: Pathways between primary production and fisheries yields of large marine ecosystems. *PLoS ONE*, **7(1)**, e28945, doi:10.1371/journal.pone.0028945.

Friedrich, T., A. Timmermann, A. Abe-Ouchi, N.R. Bates, M.O. Chikamoto, M.J. Church, J.E. Dore, D.K. Gledhill, M. González-Dávila, M. Heinemann, T. Ilyina, J.H. Jungclaus, E. McLeod, A. Mouchet, and J.M. Santana-Casiano, 2012: Detecting regional anthropogenic trends in ocean acidification against natural variability. *Nature Climate Change*, **2(3)**, 167-171.

Frommel, A.Y., R. Maneja, D. Lowe, A.M. Malzahn, A.J. Geffen, A. Folkvord, U. Piatkowski, T.B.H. Reusch, and C. Clemmesen, 2012: Severe tissue damage in Atlantic cod larvae under increasing ocean acidification. *Nature Climate Change*, **2(1)**, 42-46.

Fu, F.-X., M.E. Warner, Y. Zhang, Y. Feng, and D.A. Hutchins, 2007: Effects of increased temperature and CO_2 on photosynthesis, growth, and elemental ratios in marine *Synechococcus* and *Prochlorococcus* (Cyanobacteria). *Journal of Phycology*, **43(3)**, 485-496.

Fu, F.-X., Y. Zhang, M.E. Warner, Y. Feng, J. Sun, and D.A. Hutchins, 2008: A comparison of future increased CO_2 and temperature effects on sympatric *Heterosigma akashiwo* and *Prorocentrum minimum*. *Harmful Algae*, **7(1)**, 76-90.

Fu, F.-X., A.R. Place, N.S. Garcia, and D.A. Hutchins, 2010: CO_2 and phosphate availability control the toxicity of the harmful bloom dinoflagellate *Karlodinium veneficum*. *Aquatic Microbial Ecology*, **59(1)**, 55-65.

Fu, F.-X., A.O. Tatters, and D.A. Hutchins, 2012: Global change and the future of harmful algal blooms in the ocean. *Marine Ecology Progress Series*, **470**, 207-233.

Fuentes, M.M.P.B., J.A. Maynard, M. Guinea, I.P. Bell, P.J. Werdell, and M. Hamann, 2009: Proxy indicators of sand temperature help project impacts of global warming on sea turtles in northern Australia. *Endangered Species Research*, **9(1)**, 33-40.

Fulton, E.A., 2011: Interesting times: winners, losers, and system shifts under climate change around Australia. *ICES Journal of Marine Science*, **68(6)**, 1329-1342.

Fulton, E.A., J.S. Link, I.C. Kaplan, M. Savina-Rolland, P. Johnson, C. Ainsworth, P. Horne, R. Gorton, R.J. Gamble, A.D.M. Smith, and D.C. Smith, 2011: Lessons in modelling and management of marine ecosystems: the Atlantis experience. *Fish and Fisheries*, **12(2)**, 171-188.

Galbraith, H., R. Jones, R. Park, J. Clough, S. Herrod-Julius, B. Harrington, and G. Page, 2005: Global climate and sea level rise: potential losses of intertidal habitat for shorebirds. In: *Bird Conservation Implementation and Integration in the Americas: Proceedings of the Third International Partners in Flight Conference, 2002, March 20-24, Asilomar, CA, Vol. 2* [Ralph, C.J. and T.D. Rich (eds.)]. General Technical Report, PSW-GTR-191, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA, USA, pp. 1119-1122.

Garcia, S.M. and A.A. Rosenberg, 2010: Food security and marine capture fisheries: characteristics, trends, drivers and future perspectives. *Philosophical Transactions of the Royal Society B*, **365(1554)**, 2869-2880.

Gardner, B., P.J. Sullivan, S. Epperly, and S.J. Morreale, 2008: Hierarchical modeling of bycatch rates of sea turtles in the western North Atlantic. *Endangered Species Research*, **5**, 279-289.

Gazeau, F., L.M. Parker, S. Comeau, J.-P. Gattuso, W.A. O'Connor, S. Martin, H.-O. Pörtner, and P.M. Ross, 2013: Impacts of ocean acidification on marine shelled molluscs. *Marine Biology*, **160(8)**, 2207-2245.

Genner, M.J., D.W. Sims, V.J. Wearmouth, E.J. Southall, A.J. Southward, P.A. Henderson, and S.J. Hawkins, 2004: Regional climatic warming drives long-term community changes of British marine fish. *Proceedings of the Royal Society B*, **271(1539)**, 655-661.

Genner, M.J., D.W. Sims, A.J. Southward, G.C. Budd, P. Masterson, M. McHugh, P. Rendle, E.J. Southall, V.J. Wearmouth, and S.J. Hawkins, 2010: Body size-dependent responses of a marine fish assemblage to climate change and fishing over a century-long scale. *Global Change Biology*, **16(2)**, 517-527.

Gibbs, S.J., P.R. Bown, J.A. Sessa, T.J. Bralower, and P.A. Wilson, 2006: Nannoplankton extinction and origination across the Paleocene-Eocene Thermal Maximum. *Science*, **314(5806)**, 1770-1773.

Gilly, W.F., U. Markaida, C.H. Baxter, B.A. Block, A. Boustany, L. Zeidberg, K. Reisenbichler, B. Robison, G. Bazzino, and C. Salinas, 2006: Vertical and horizontal migrations by the jumbo squid *Dosidicus gigas* revealed by electronic tagging. *Marine Ecology Progress Series*, **324**, 1-17.

Gilly, W.F., J.M. Beman, S.Y. Litvin, and B.H. Robison, 2013: Oceanographic and biological effects of shoaling of the oxygen minimum zone. *Annual Review of Marine Science*, **5**, 393-420.

Giordano, M., J. Beardall, and J.A. Raven, 2005: CO_2 concentrating mechanisms in algae: mechanisms, environmental modulation, and evolution. *Annual Review of Plant Biology*, **56**, 99-131.

Giovannoni, S.J. and K.L. Vergin, 2012: Seasonality in ocean microbial communities. *Science*, **335(6069)**, 671-676.

Glynn, P.W. and L. D'Croz, 1990: Experimental evidence for high temperature stress as the cause of El Niño-coincident coral mortality. *Coral Reefs*, **8(4)**, 181-191.

Godfrey, M.H., A.F. D'Amato, M.Â. Marcovaldi, and N. Mrosovsky, 1999: Pivotal temperature and predicted sex ratios for hatchling hawksbill turtles from Brazil. *Canadian Journal of Zoology*, **77(9)**, 1465-1473.

Gómez, I., A. Wulff, M. Roleda, P. Huovinen, U. Karsten, M.L. Quartino, K. Dunton, and C. Wiencke, 2011: Light and temperature demands of benthic algae in the polar regions. In: *Biology of Polar Benthic Algae* [Wiencke, C. (ed.)]. de Gruyter, Berlin, Germany, pp. 195-220.

González-Taboada, F. and R. Anadón, 2012: Patterns of change in sea surface temperature in the North Atlantic during the last three decades: beyond mean trends. *Climatic Change*, **115(2)**, 419-431.

Gooday, A.J., B.J. Bett, E. Escobar, B. Ingole, L.A. Levin, C. Neira, A.V. Raman, and J. Sellanes, 2010: Habitat heterogeneity and its relationship to biodiversity in oxygen minimum zones. *Marine Ecology*, **31**, 125-147.

Gooding, R.A., C.D.G. Harley, and E. Tang, 2009: Elevated water temperature and carbon dioxide concentration increase the growth of a keystone echinoderm. *Proceedings of the National Academy of Sciences of the United States of America*, **106(23)**, 9316-9321.

Goreau, T.J. and R.L. Hayes, 1994: Coral bleaching and ocean "Hot Spots". *Ambio*, **23(3)**, 176-180.

Granier, C., U. Niemeier, J.H. Jungclaus, L. Emmons, P. Hess, J.F. Lamarque, S. Walters, and G.P. Brasseur, 2006: Ozone pollution from future ship traffic in the Arctic northern passages. *Geophysical Research Letters*, **33(13)**, L13807, doi:10.1029/2006GL026180.

Gravelle, G. and N. Mimura, 2008: Vulnerability assessment of sea-level rise in Viti Levu, Fiji Islands. *Sustainability Science*, **3(2)**, 171-180.

Gray, J.S., R.S.S. Wu, and Y.Y. Or, 2002: Effects of hypoxia and organic enrichment on the coastal marine environment. *Marine Ecology Progress Series*, **238**, 249-279.

Green, J.L., B.J.M. Bohannan, and R.J. Whitaker, 2008: Microbial biogeography: from taxonomy to traits. *Science*, **320(5879)**, 1039-1043.

Greene, C.H. and A.J. Pershing, 2003: The flip-side of the North Atlantic Oscillation and modal shifts in slope-water circulation patterns. *Limnology and Oceanography*, **48(1)**, 319-322.

Greene, C.H. and A.J. Pershing, 2007: Climate drives sea change. *Science*, **315(5815)**, 1084-1085.

Greene, C.H., A.J. Pershing, R.D. Kenney, and J.W. Jossi, 2003: Impact of climate variability on the recovery of endangered North Atlantic right whales. *Oceanography*, **16(4)**, 98-103.

Grémillet, D. and T. Boulinier, 2009: Spatial ecology and conservation of seabirds facing global climate change: a review. *Marine Ecology Progress Series*, **391**, 121-137.

Grieshaber, M., I. Hardewig, U. Kreutzer, and H.-O. Pörtner, 1994: Physiological and metabolic responses to hypoxia in invertebrates. In: *Reviews of Physiology, Biochemistry and Pharmacology* [Blaustein, M.P., H. Grunicke, E. Habermann, D. Pette, H. Reuter, B. Sakmann, M. Schweiger, E. Weibel, and E.M. Wright (eds.)]. Springer, Berlin Heidelberg, Germany, pp. 43-147.

Griffith, G.P., E.A. Fulton, and A.J. Richardson, 2011: Effects of fishing and acidification-related benthic mortality on the southeast Australian marine ecosystem. *Global Change Biology*, **17(10)**, 3058-3074.

Griffith, G.P., E.A. Fulton, R. Gorton, and A.J. Richardson, 2012: Predicting interactions among fishing, ocean warming, and ocean acidification in a marine system with whole-ecosystem models. *Conservation Biology*, **26(6)**, 1145-1152.

Grossart, H.P., M. Allgaier, U. Passow, and U. Riebesell, 2006: Testing the effect of CO_2 concentration on the dynamics of marine heterotrophic bacterioplankton. *Limnology and Oceanography*, **51(1)**, 1-11.

Gruber, N., 2011: Warming up, turning sour, losing breath: ocean biogeochemistry under global change. *Philosophical Transactions of the Royal Society A*, **369(1943)**, 1980-1996.

Guinotte, J.M., J. Orr, S. Cairns, A. Freiwald, L. Morgan, and R. George, 2006: Will human-induced changes in seawater chemistry alter the distribution of deep-sea scleractinian corals? *Frontiers in Ecology and the Environment*, **4(3)**, 141-146.

Gutowska, M.A., H.-O. Pörtner, and F. Melzner, 2008: Growth and calcification in the cephalopod *Sepia officinalis* under elevated seawater pCO_2. *Marine Ecology Progress Series*, **373**, 303-309.

Haines, A., R.S. Kovats, D. Campbell-Lendrum, and C. Corvalan, 2006: Climate change and human health: impacts, vulnerability, and mitigation. *The Lancet*, **367(9528)**, 2101-2109.

Hales, S., P. Weinstein, and A. Woodward, 1999: Ciguatera (fish poisoning), El Niño, and Pacific sea surface temperatures. *Ecosystem Health*, **5(1)**, 20-25.

Halfar, J., S. Hetzinger, W. Adey, T. Zack, G. Gamboa, B. Kunz, B. Williams, and D.E. Jacob, 2011: Coralline algal growth-increment widths archive North Atlantic climate variability. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **302(1-2)**, 71-80.

Hall-Spencer, J.M., R. Rodolfo-Metalpa, S. Martin, E. Ransome, M. Fine, S.M. Turner, S.J. Rowley, D. Tedesco, and M.-C. Buia, 2008: Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. *Nature*, **454(7200)**, 96-99.

Hallegraeff, G.M., 2010: Ocean climate change, phytoplankton community responses, and harmful algal blooms: a formidable predictive challenge. *Journal of Phycology*, **46(2)**, 220-235.

Hannah, C., A. Vezina, and M. St. John, 2010: The case for marine ecosystem models of intermediate complexity. *Progress in Oceanography*, **84(1-2)**, 121-128.

Hannesson, R., 2007: Global warming and fish migrations. *Natural Resource Modeling*, **20(2)**, 301-319.

Hansen, P.J., N. Lundholm, and B. Rost, 2007: Growth limitation in marine red-tide dinoflagellates: effects of pH versus inorganic carbon availability. *Marine Ecology Progress Series*, **334**, 63-71.

Hare, J.A., M.J. Wuenschel, and M.E. Kimball, 2012: Projecting range limits with coupled thermal tolerance –climate change models: an example based on gray snapper (*Lutjanus griseus*) along the U.S. east coast. *PLoS ONE*, **7(12)**, e52294, doi:10.1371/journal.pone.0052294.

Harley, C.D.G., 2011: Climate change, keystone predation, and biodiversity loss. *Science*, **334(6059)**, 1124-1127.

Harley, C.D.G., K.M. Anderson, K.W. Demes, J.P. Jorve, R.L. Kordas, T.A. Coyle, and M.H. Graham, 2012: Effects of climate change on global seaweed communities. *Journal of Phycology*, **48(5)**, 1064-1078.

Harvell, D., S. Altizer, I.M. Cattadori, L. Harrington, and E. Weil, 2009: Climate change and wildlife diseases: when does the host matter the most? *Ecology*, **90(4)**, 912-920.

Harvey, B.P., D. Gwynn-Jones, and P.J. Moore, 2013: Meta-analysis reveals complex marine biological responses to the interactive effects of ocean acidification and warming. *Ecology and Evolution*, **3(4)**, 1016-1030.

Hashioka, T. and Y. Yamanaka, 2007: Ecosystem change in the western North Pacific associated with global warming using 3D-NEMURO. *Ecological Modelling*, **202(1-2)**, 95-104.

Hawkes, L.A., A.C. Broderick, M.H. Godfrey, and B.J. Godley, 2009: Climate change and marine turtles. *Endangered Species Research*, **7(2)**, 137-154.

Hawkins, S.J., 2012: Marine conservation in a rapidly changing world. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **22(3)**, 281-287.

Hays, G.C., A.C. Broderick, F. Glen, and B.J. Godley, 2003: Climate change and sea turtles: a 150-year reconstruction of incubation temperatures at a major marine turtle rookery. *Global Change Biology*, **9(4)**, 642-646.

Haywood, A.M., M.A. Chandler, P.J. Valdes, U. Salzmann, D.J. Lunt, and H.J. Dowsett, 2009: Comparison of mid-Pliocene climate predictions produced by the HadAM3 and GCMAM3 General Circulation Models. *Global and Planetary Change*, **66(3-4)**, 208-224.

Hazen, E.L., J.K. Craig, C.P. Good, and L.B. Crowder, 2009: Vertical distribution of fish biomass in hypoxic waters on the Gulf of Mexico shelf. *Marine Ecology Progress Series*, **375**, 195-207.

Hazen, E.L., S. Jorgensen, R.R. Rykaczewski, S.J. Bograd, D.G. Foley, I.D. Jonsen, S.A. Shaffer, J.P. Dunne, D.P. Costa, L.B. Crowder, and B.A. Block, 2013: Predicted habitat shifts of Pacific top predators in a changing climate. *Nature Climate Change*, **3**, 234-238.

Head, E.J.H. and P. Pepin, 2010: Spatial and inter-decadal variability in plankton abundance and composition in the Northwest Atlantic (1958–2006). *Journal of Plankton Research*, **32(12)**, 1633-1648.

Heath, M., M. Edwards, R. Furness, J. Pinnegar, and S. Wanless, 2009: A view from above: changing seas, seabirds and food sources. In: *Marine Climate Change Ecosystem Linkages Report Card* [Baxter, J.M., P.J. Buckley, and M.T. Frost (eds.)]. Marine Climate Change Impacts Partnership (MCCIP), Lowestoft, UK, 24 pp.

Heisler, N. (ed.), 1986: *Acid-base Regulation in Animals*. Elsevier, Amsterdam, Netherlands, 492 pp.

Helm, K.P., N.L. Bindoff, and J.A. Church, 2010: Changes in the global hydrological-cycle inferred from ocean salinity. *Geophysical Research Letters*, **37(18)**, L18701, doi:10.1029/2010GL044222.

Henson, S., J.L. Sarmiento, J.P. Dunne, L. Bopp, I. Lima, S.C. Doney, J. John, and C. Beaulieu, 2010: Detection of anthropogenic climate change in satellite records of ocean chlorophyll and productivity. *Biogeosciences*, **7(2)**, 621-640.

Henson, S., H. Cole, C. Beaulieu, and A. Yool, 2013: The impact of global warming on seasonality of ocean primary production. *Biogeosciences*, **10**, 4357-4369.

Higginson, M.J., M.A. Altabet, D.W. Murray, R.W. Murray, and T.D. Herbert, 2004: Geochemical evidence for abrupt changes in relative strength of the Arabian monsoons during a stadial/interstadial climate transition. *Geochimica et Cosmochimica Acta*, **68(19)**, 3807-3826.

Hill, V.J., P.A. Matrai, E. Olson, S. Suttles, M. Steele, L.A. Codispoti, and R.C. Zimmerman, 2013: Synthesis of integrated primary production in the Arctic Ocean: II. *In situ* and remotely sensed estimates. *Progress in Oceanography*, **110**, 107-125.

Hinder, S.L., G.C. Hays, M. Edwards, E.C. Roberts, A.W. Walne, and M.B. Gravenor, 2012: Changes in marine dinoflagellate and diatom abundance under climate change. *Nature Climate Change*, **2(4)**, 271-275.

Hoegh-Guldberg, O., 1999: Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research*, **50(8)**, 839-866.

Hoegh-Guldberg, O., 2011: Coral reef ecosystems and anthropogenic climate change. *Regional Environmental Change*, **11**, 215-227.

Hoegh-Guldberg, O. and J.F. Bruno, 2010: The impact of climate change on the world's marine ecosystems. *Science*, **328(5985)**, 1523-1528.

Hoegh-Guldberg, O. and B. Salvat, 1995: Periodic mass-bleaching and elevated sea temperatures: bleaching of outer reef slope communities in Moorea, French Polynesia. *Marine Ecology Progress Series*, **121**, 181-190.

Hoegh-Guldberg, O. and G.J. Smith, 1989: The effect of sudden changes in temperature, light and salinity on the population density and export of zooxanthellae from the reef corals *Stylophora pistillata* Esper and *Seriatopora hystrix* Dana. *Journal of Experimental Marine Biology and Ecology*, **129(3)**, 279-303.

Hoel, A.H., 2009: *Best Practices in Ecosystem Based Ocean Management in the Arctic*. Norsk Polarinstitutt, Tromsø, Norway, 116 pp.

Hoffmann, L.J., E. Breitbarth, P.W. Boyd, and K.A. Hunter, 2012: Influence of ocean warming and acidification on trace metal biogeochemistry. *Marine Ecology Progress Series*, **470**, 191-205.

Holcomb, M., A.L. Cohen, and D.C. McCorkle, 2012: An investigation of the calcification response of the scleractinian coral *Astrangia poculata* to elevated pCO_2 and the effects of nutrients, zooxanthellae and gender. *Biogeosciences*, **9(1)**, 29-39.

Holt, J., S. Wakelin, J. Lowe, and J. Tinker, 2010: The potential impacts of climate change on the hydrography of the northwest European continental shelf. *Progress in Oceanography*, **86(3-4)**, 361-379.

Hönisch, B., A. Ridgwell, D.N. Schmidt, E. Thomas, S.J. Gibbs, A. Sluijs, R. Zeebe, L. Kump, R.C. Martindale, S.E. Greene, W. Kiessling, J. Ries, J.C. Zachos, D.L. Royer, S. Barker, T.M. Marchitto, R. Moyer, C. Pelejero, P. Ziveri, G.L. Foster, and B. Williams, 2012: The geological record of ocean acidification. *Science*, **335(6072)**, 1058-1063.

Hoppe, C.J.M., G. Langer, and B. Rost, 2011: *Emiliania huxleyi* shows identical responses to elevated pCO_2 in TA and DIC manipulations. *Journal of Experimental Marine Biology and Ecology*, **406(1-2)**, 54-62.

Hoppe, H.-G., K. Gocke, R. Koppe, and C. Begler, 2002: Bacterial growth and primary production along a north-south transect of the Atlantic Ocean. *Nature*, **416(6877)**, 168-171.

House, K.Z., C.H. House, D.P. Schrag, and M.J. Aziz, 2007: Electrochemical acceleration of chemical weathering as an energetically feasible approach to mitigating anthropogenic climate change. *Environmental Science & Technology*, **41(24)**, 8464-8470.

Howarth, R., F. Chan, D.J. Conley, J. Garnier, S.C. Doney, R. Marino, and G. Billen, 2011: Coupled biogeochemical cycles: eutrophication and hypoxia in temperate estuaries and coastal marine ecosystems. *Frontiers in Ecology and the Environment*, **9(1)**, 18-26.

Howells, E.J., V.H. Beltran, N.W. Larsen, L.K. Bay, B.L. Willis, and M.J.H. van Oppen, 2012: Coral thermal tolerance shaped by local adaptation of photosymbionts. *Nature Climate Change*, **2(2)**, 116-120.

Hsieh, C.-H., C.S. Reiss, J.R. Hunter, J.R. Beddington, R.M. May, and G. Sugihara, 2006: Fishing elevates variability in the abundance of exploited species. *Nature*, **443(7113)**, 859-862.

Hsieh, C.-H., C.S. Reiss, R.P. Hewitt, and G. Sugihara, 2008: Spatial analysis shows that fishing enhances the climatic sensitivity of marine fishes. *Canadian Journal of Fisheries and Aquatic Sciences*, **65(5)**, 947-961.

Huber, R., T.A. Langworthy, H. König, M. Thomm, C.R. Woese, U.B. Sleytr, and K.O. Stetter, 1986: *Thermotoga maritima* sp. nov. represents a new genus of unique extremely thermophilic eubacteria growing up to 90°C. *Archives of Microbiology*, **144(4)**, 324-333.

Huey, R.B. and J.G. Kingsolver, 1989: Evolution of thermal sensitivity of ectotherm performance. *Trends in Ecology and Evolution*, **4(5)**, 131-135.

Hughes, L., 2000: Biological consequences of global warming: is the signal already apparent? *Trends in Ecology and Evolution*, **15(2)**, 56-61.

Hughes, R.G., 2004: Climate change and loss of saltmarshes: consequences for birds. *Ibis*, **146**, 21-28.

Hughes, T.P., A.H. Baird, E.A. Dinsdale, N.A. Moltschaniwskyj, M.S. Pratchett, J.E. Tanner, and B.L. Willis, 2012: Assembly rules of reef corals are flexible along a steep climatic gradient. *Current Biology*, **22(8)**, 736-741.

Hunt, B.P.V., E.A. Pakhomov, G.W. Hosie, V. Siegel, P. Ward, and K. Bernard, 2008: Pteropods in Southern Ocean ecosystems. *Progress in Oceanography*, **78(3)**, 193-221.

Huntley, B., R.E. Green, Y.C. Collingham, and S.G. Willis, 2007: *A Climatic Atlas of European Breeding Birds*. Lynx Editions, Barcelona, Spain, 521 pp.

Hutchins, D.A., F.-X. Fu, Y. Zhang, M.E. Warner, Y. Feng, K. Portune, P.W. Bernhardt, and M.R. Mulholland, 2007: CO_2 control of *Trichodesmium* N_2 fixation, photosynthesis, growth rates, and elemental ratios: implications for past, present, and future ocean biogeochemistry. *Limnology and Oceanography*, **52(4)**, 1293-1304.

Hutchins, D.A., M.R. Mulholland, and F.-X. Fu, 2009: Nutrient cycles and marine microbes in a CO_2-enriched ocean. *Oceanography*, **22(4)**, 128-145.

Hutchins, D.A., F.-X. Fu, E.A. Webb, N. Walworth, and A. Tagliabue, 2013: Taxon-specific response of marine nitrogen fixers to elevated carbon dioxide concentrations. *Nature Geoscience*, **6**, 790-795.

Iglesias-Rodriguez, M.D., P.R. Halloran, R.E. Rickaby, I.R. Hall, E. Colmenero-Hidalgo, J.R. Gittins, D.R. Green, T. Tyrrell, S.J. Gibbs, P. von Dassow, E. Rehm, E.V. Armbrust, and K.P. Boessenkool, 2008: Phytoplankton calcification in a high-CO_2 world. *Science*, **320(5874)**, 336-340.

Ilyina, T., R.E. Zeebe, and P.G. Brewer, 2010: Future ocean increasingly transparent to low-frequency sound owing to carbon dioxide emissions. *Nature Geoscience*, **3(1)**, 18-22.

IPCC, 2000: *Emissions Scenarios.* A *Special Report of Working Group III of the Intergovernmental Panel on Climate Change* [Nakićenović, N. and R. Swart (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 570 pp.

IPCC, 2012a: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. A *Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 594 pp.

IPCC, 2012b: *Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Geoengineering* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, C. Field, V. Barros, T.F. Stocker, Q. Dahe, J. Minx, K. Mach, G.-K. Plattner, S. Schlömer, G. Hansen, and M. Mastrandrea (eds.)]. IPCC Working Group III Technical Support Unit, Potsdam Institute for Climate Impact Research, Potsdam, Germany, 99 pp.

Ishimatsu, A. and A. Dissanayake, 2010: Life threatened in acidic coastal waters. In: *Coastal Environmental and Ecosystem Issues of the East China Sea* [Ishimatsu, A. and H.-J. Lie (eds.)]. Terra Scientific Publishing Company (TERRAPUB) and Nagasaki University, Nagasaki, Japan, pp. 283-303.

Ishimatsu, A., M. Hayashi, and T. Kikkawa, 2008: Fishes in high-CO_2, acidified oceans. *Marine Ecology Progress Series*, **373**, 295-302.

Ito, S., K.A. Rose, A.J. Miller, K. Drinkwater, K. Brander, J.E. Overland, S. Sundby, E. Curchitser, J.W. Hurrell, and Y. Yamanaka, 2010: Ocean ecosystem responses to future global change scenarios: a way forward. In: *Global Change and Marine Ecosystems* [Barange, M., J.G. Field, R.P. Harris, E.E. Hofmann, R.I. Perry, and F. Werner (eds.)]. Oxford University Press, Oxford, UK, pp. 287-322.

Jaccard, S.L. and E.D. Galbraith, 2012: Large climate-driven changes of oceanic oxygen concentrations during the last deglaciation. *Nature Geoscience*, **5(2)**, 151-156.

Jackson, G.A. and A.B. Burd, 2001: A model for the distribution of particle flux in the mid-water column controlled by subsurface biotic interactions. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **49(1-3)**, 193-217.

Jackson, J.B.C. and K.G. Johnson, 2000: Life in the last few million years. *Paleobiology*, **26(4)**, 221-235.

Jacobs, S.S. and C.F. Giulivi, 2010: Large multidecadal salinity trends near the Pacific-Antarctic continental margin. *Journal of Climate*, **23(17)**, 4508-4524.

Jantzen, C., V. Häussermann, G. Försterra, J. Laudien, M. Ardelan, S. Maier, and C. Richter, 2013: Occurrence of a cold-water coral along natural pH gradients (Patagonia, Chile). *Marine Biology*, **160(10)**, 2597-2607.

Jarre, A. and L.J. Shannon, 2010: Regime shifts: physical-biological interactions under climatic and anthropogenic pressures. In: *Marine Ecocystems and Global Change* [Barange, M., J.G. Field, R.P. Harris, E.E. Hofmann, R.I. Perry, and F. Werner (eds.)]. Oxford University Press, Oxford, UK, pp. 215-216.

Jenkyns, H.C., 2010: Geochemistry of oceanic anoxic events. *Geochemistry Geophysics Geosystems*, **11(3)**, Q03004, doi:10.1029/2009GC002788.

Jenouvrier, S., M. Holland, J. Stroeve, C. Barbraud, H. Weimerskirch, M. Serreze, and H. Caswell, 2012: Effects of climate change on an emperor penguin population: analysis of coupled demographic and climate models. *Global Change Biology*, **18(9)**, 2756-2770.

Jessen, G.L., R.A. Quiñones, and R.R. González, 2009: Aerobic and anaerobic enzymatic activity and allometric scaling of the deep benthic polychaete *Hyalinoecia artifex* (Polychaeta: Onuphidae). *Journal of the Marine Biological Association of the United Kingdom*, **89(6)**, 1171-1175.

Jin, D., E. Thunberg, and P. Hoagland, 2008: Economic impact of the 2005 red tide event on commercial shellfish fisheries in New England. *Ocean & Coastal Management*, **51(5)**, 420-429.

Jin, X. and N. Gruber, 2003: Offsetting the radiative benefit of ocean iron fertilization by enhancing N_2O emissions. *Geophysical Research Letters*, **30(24)**, 2249, doi:10.1029/2003GL018458.

Johns, D.G., M. Edwards, and S.D. Batten, 2001: Arctic boreal plankton species in the Northwest Atlantic. *Canadian Journal of Fisheries and Aquatic Sciences*, **58(11)**, 2121-2124.

Johns, D.G., M. Edwards, A. Richardson, and J.I. Spicer, 2003: Increased blooms of a dinoflagellate in the NW Atlantic. *Marine Ecology Progress Series*, **265**, 283-287.

Johnson, K.S., S.C. Riser, and D.M. Karl, 2010: Nitrate supply from deep to near-surface waters of the North Pacific subtropical gyre. *Nature*, **465(7301)**, 1062-1065.

Joint, I., S.C. Doney, and D.M. Karl, 2011: Will ocean acidification affect marine microbes? *ISME Journal*, **5(1)**, 1-7, doi:10.1038/ismej.2010.79.

Jones, A.M., R. Berkelmans, M.J.H. van Oppen, J.C. Mieog, and W. Sinclair, 2008: A community change in the algal endosymbionts of a scleractinian coral following a natural bleaching event: field evidence of acclimatization. *Proceedings of the Royal Society B*, **275(1641)**, 1359-1365.

Jones, M.C., S.R. Dye, J.A. Fernandes, T.L. Frölicher, J.K. Pinnegar, R. Warren, and W.W.L. Cheung, 2013: Predicting the impact of climate change on threatened species in UK waters. *PLoS ONE*, **8(1)**, e54216, doi:10.1371/journal.pone.0054216.

Jones, P.D., M. New, D.E. Parker, S. Martin, and I.G. Rigor, 1999: Surface air temperature and its changes over the past 150 years. *Reviews of Geophysics*, **37(2)**, 173-199.

Jones, R.J., O. Hoegh-Guldberg, A.W.D. Larkum, and U. Schreiber, 1998: Temperature-induced bleaching of corals begins with impairment of the CO_2 fixation mechanism in zooxanthellae. *Plant, Cell and Environment*, **21(12)**, 1219-1230.

Jutfelt, F., K. Bresolin de Souza, A. Vuylsteke, and J. Sturve, 2013: Behavioural disturbances in a temperate fish exposed to sustained high-CO_2 levels. *PLoS ONE*, **8(6)**, e65825, doi:10.1371/journal.pone.0065825.

Kaniewska, P., P.R. Campbell, D.I. Kline, M. Rodriguez-Lanetty, D.J. Miller, S. Dove, and O. Hoegh-Guldberg, 2012: Major cellular and physiological impacts of ocean acidification on a reef building coral. *PLoS ONE*, **7(4)**, e34659, doi:10.1371/journal.pone.0034659.

Karl, D.M., R.R. Bidigare, and R.M. Letelier, 2001: Long-term changes in plankton community structure and productivity in the North Pacific Subtropical Gyre: the domain shift hypothesis. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **48(8-9)**, 1449-1470.

Karl, D.M., N. Bates, S. Emerson, P.J. Harrison, C. Jeandel, O. Llinás, K.K. Liu, J.-C. Matry, A.F. Michaels, J.C. Miquel, S. Neuer, Y. Nojiri, and C.S. Wong, 2003: Temporal studies of biogeochemical processes determined from ocean time-series observations during the JGOFS era. In: *Ocean Biogeochemistry: The Role of the Ocean Carbon Cycle in Global Change* [Fasham, M.J.R. (ed.)]. Springer, Berlin, Germany, pp. 239-267.

Karstensen, J., L. Stramma, and M. Visbeck, 2008: Oxygen minimum zones in the eastern tropical Atlantic and Pacific oceans. *Progress in Oceanography*, **77(4)**, 331-350.

Kaschner, K., D.P. Tittensor, J. Ready, T. Gerrodette, and B. Worm, 2011: Current and future patterns of global marine mammal biodiversity. *PLoS ONE*, **6(5)**, e19653, doi:10.1371/journal.pone.0019653.

Kashefi, K. and D.R. Lovley, 2003: Extending the upper temperature limit for life. *Science*, **301(5635)**, 934.

Katsikatsou, M., A. Anestis, H.-O. Pörtner, A. Vratsistas, K. Aligizaki, and B. Michaelidis, 2012: Field studies and projections of climate change effects on the bearded horse mussel *Modiolus barbatus* in the Gulf of Thermaikos, Greece. *Marine Ecology Progress Series*, **449**, 183-196.

Keeling, C.D., S.C. Piper, R.B. Bacastow, M. Wahlen, T.P. Whorf, M. Heimann, and H.A. Meijer, 2005: Atmospheric CO_2 and $^{13}CO_2$ exchange with the terrestrial biosphere and oceans from 1978 to 2000: observations and carbon cycle implications. In: *A History of Atmospheric CO_2 and its Effects on Plants, Animals, and Ecosystems* [Baldwin, I.T., M.M. Caldwell, G. Heldmaier, R.B. Jackson, O.L. Lange, H.A. Mooney, E.-D. Schulze, and U. Sommer (eds.)]. Springer, New York, NY, USA, pp. 83-113.

Keeling, R.F., A. Körtzinger, and N. Gruber, 2010: Ocean deoxygenation in a warming world. *Annual Review of Marine Science*, **2(1)**, 199-229.

Kelly, M.W., E. Sanford, and R.K. Grosberg, 2012: Limited potential for adaptation to climate change in a broadly distributed marine crustacean. *Proceedings of the Royal Society B*, **279(1727)**, 349-356.

Kennett, J.P. and L.D. Stott, 1991: Abrupt deep-sea warming, palaeoceanographic changes and benthic extinctions at the end of the Paleocene. *Nature*, **353(6341)**, 225-229.

Kiessling, W. and C. Simpson, 2011: On the potential for ocean acidification to be a general cause of ancient reef crises. *Global Change Biology*, **17(1)**, 56-67.

Kiessling, W., C. Simpson, B. Beck, H. Mewis, and J.M. Pandolfi, 2012: Equatorial decline of reef corals during the last Pleistocene interglacial. *Proceedings of the National Academy of Sciences of the United States of America*, **109(52)**, 21378-21383.

Kim, J.-M., K. Lee, K. Shin, E.J. Yang, A. Engel, D.M. Karl, and H.-C. Kim, 2011: Shifts in biogenic carbon flow from particulate to dissolved forms under high carbon dioxide and warm ocean conditions. *Geophysical Research Letters*, **38(8)**, L08612, doi:10.1029/2011GL047346.

Kirby, R.R. and G. Beaugrand, 2009: Trophic amplification of climate warming. *Proceedings of the Royal Society B*, **276(1676)**, 4095-4103.

Kirby, R.R., G. Beaugrand, and J.A. Lindley, 2009: Synergistic effects of climate and fishing in a marine ecosystem. *Ecosystems*, **12(4)**, 548-561.

Kirchman, D.L., X.A. Morán, and H. Ducklow, 2009: Microbial growth in the polar oceans – role of temperature and potential impact of climate change. *Nature Reviews Microbiology*, **7(6)**, 451-459.

Kirk, J.T.O., 1994: *Light and Photosynthesis in Aquatic Ecosystems*. Cambridge University Press, Cambridge, UK, 662 pp.

Klaas, C. and D.E. Archer, 2002: Association of sinking organic matter with various types of mineral ballast in the deep sea: implications for the rain ratio. *Global Biogeochemical Cycles*, **16(4)**, 1116, doi:10.1029/2001GB001765.

Kleypas, J.A. and C. Langdon, 2006: Coral reefs and changing seawater chemistry. In: *Coral Reefs and Climate Change: Science and Management* [Phinney, J., O. Hoegh-Guldberg, J. Kleypas, W. Skirving, and A.E. Strong (eds.)]. American Geophysical Union, Washington, DC, USA, pp. 73-110.

Knies, J.L., R. Izem, K.L. Supler, J.G. Kingsolver, and C.L. Burch, 2006: The genetic basis of thermal reaction norm evolution in lab and natural phage populations. *PLoS Biology*, **4(7)**, e201, doi:10.1371/journal.pbio.0040201.

Knoll, A. and W.W. Fischer, 2011: Skeletons and ocean chemistry: the long view. In: *Ocean Acidification* [Gattuso, J.-P. and L. Hansson (eds.)]. Oxford University Press, Oxford, UK, pp. 67-82.

Knoll, A., R.K. Bambach, J.L. Payne, S. Pruss, and W.W. Fischer, 2007: Paleophysiology and end-Permian mass extinction. *Earth and Planetary Science Letters*, **256(3-4)**, 295-313.

Köhler, P., J. Hartmann, and D.A. Wolf-Gladrow, 2010: Geoengineering potential of artificially enhanced silicate weathering of olivine. *Proceedings of the National Academy of Sciences of the United States of America*, **107(47)**, 20228-20233.

Koslow, J.A., R. Goericke, A. Lara-Lopez, and W. Watson, 2011: Impact of declining intermediate-water oxygen on deepwater fishes in the California Current. *Marine Ecology Progress Series*, **436**, 207-218.

Kovach, R.P., A.J. Gharrett, and D.A. Tallmon, 2012: Genetic change for earlier migration timing in a pink salmon population. *Proceedings of the Royal Society B*, **279(1743)**, 3870-3878.

Kovats, R.S., M.J. Bouma, S. Hajat, E. Worrall, and A. Haines, 2003: El Niño and health. *The Lancet*, **362(9394)**, 1481-1489.

Kranz, S.A., O. Levitan, K.U. Richter, O. Prášil, I. Berman-Frank, and B. Rost, 2010: Combined effects of CO_2 and light on the N_2-fixing cyanobacterium *Trichodesmium* IMS101: physiological responses. *Plant Physiology*, **154(1)**, 334-345.

Kranz, S.A., M. Eichner, and B. Rost, 2011: Interactions between CCM and N_2 fixation in *Trichodesmium*. *Photosynthesis Research*, **109(1-3)**, 73-84.

Krause, E., A. Wichels, L. Giménez, M. Lunau, M.B. Schilhabel, and G. Gerdts, 2012: Small changes in pH have direct effects on marine bacterial community composition: a microcosm approach. *PLoS ONE*, **7(10)**, e47035, doi:10.1371/journal.pone.0047035.

Kroeker, K.J., F. Micheli, M.C. Gambi, and T.R. Martz, 2011: Divergent ecosystem responses within a benthic marine community to ocean acidification. *Proceedings of the National Academy of Sciences of the United States of America*, **108(35)**, 14515-14520.

Kroeker, K.J., R.L. Kordas, R. Crim, I.E. Hendriks, L. Ramajo, G.S. Singh, C.M. Duarte, and J.-P. Gattuso, 2013: Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. *Global Change Biology*, **19(6)**, 1884-1896.

Kübler, J.E. and I.R. Davison, 1995: Thermal acclimation of light use characteristics of *Chondrus crispus* (Rhodophyta). *European Journal of Phycology*, **30(3)**, 189-195.

Kurihara, H. and Y. Shirayama, 2004: Effects of increased amospheric CO_2 on sea urchin early development. *Marine Ecology Progress Series*, **274**, 161-169.

La Sorte, F.A. and W. Jetz, 2010: Avian distributions under climate change: towards improved projections. *Journal of Experimental Biology*, **213(6)**, 862-869.

Lafferty, K.D., 2009: Calling for an ecological approach to studying climate change and infectious diseases. *Ecology*, **90(4)**, 932-933.

Laidre, K.L., I. Stirling, L.F. Lowry, O. Wiig, M.P. Heide-Jørgensen, and S.H. Ferguson, 2008: Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecological Applications*, **18(Suppl 2)**, S97-S125.

Lam, P.J. and J.K.B. Bishop, 2008: The continental margin is a key source of iron to the HNLC North Pacific Ocean. *Geophysical Research Letters*, **35(7)**, L07608, doi:10.1029/2008GL033294.

Lambert, E., C. Hunter, G.J. Pierce, and C.D. MacLeod, 2010: Sustainable whale-watching tourism and climate change: towards a framework of resilience. *Journal of Sustainable Tourism*, **18(3)**, 409-427.

Langdon, C. and M.J. Atkinson, 2005: Effect of elevated pCO_2 on photosynthesis and calcification of corals and interactions with seasonal change in temperature/irradiance and nutrient enrichment. *Journal of Geophysical Research*, **110(C9)**, C09S07, doi:10.1029/2004JC002576.

Langenbuch, M. and H.-O. Pörtner, 2002: Changes in metabolic rate and N excretion in the marine invertebrate *Sipunculus nudus* under conditions of environmental hypercapnia: identifying effective acid-base variables. *Journal of Experimental Biology*, **205(8)**, 1153-1160.

Langenbuch, M. and H.-O. Pörtner, 2003: Energy budget of hepatocytes from Antarctic fish (*Pachycara brachycephalum* and *Lepidonotothen kempi*) as a function of ambient CO_2: pH-dependent limitations of cellular protein biosynthesis? *Journal of Experimental Biology*, **206(22)**, 3895-3903.

Langenbuch, M., C. Bock, D. Leibfritz, and H.-O. Pörtner, 2006: Effects of environmental hypercapnia on animal physiology: a ^{13}C NMR study of protein synthesis rates in the marine invertebrate *Sipunculus nudus*. *Comparative Biochemistry and Physiology A: Molecular and Integrative Physiology*, **144(4)**, 479-484.

Langer, G., M. Geisen, K.-H. Baumann, J. Kläs, U. Riebesell, S. Thoms, and J.R. Young, 2006: Species-specific responses of calcifying algae to changing seawater carbonate chemistry. *Geochemistry Geophysics Geosystems*, **7(9)**, Q09006.

Langer, G., G. Nehrke, I. Probert, J. Ly, and P. Ziveri, 2009: Strain-specific responses of *Emiliania huxleyi* to changing seawater carbonate chemistry. *Biogeosciences*, **6(11)**, 2637-2646.

Langer, G., I. Probert, G. Nehrke, and P. Ziveri, 2011: The morphological response of *Emiliania huxleyi* to seawater carbonate chemistry changes: an inter-strain comparison. *Journal of Nannoplankton Research*, **32(1)**, 27-32.

Lauer, A., V. Eyring, J.J. Corbett, C.F. Wang, and J.J. Winebrake, 2009: Assessment of near-future policy instruments for oceangoing shipping: impact on atmospheric aerosol burdens and the Earth's radiation budget. *Environmental Science & Technology*, **43(15)**, 5592-5598.

Lavaniegos, B.E. and M.D. Ohman, 2003: Long-term changes in pelagic tunicates of the California Current. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **50(14-16)**, 2473-2498.

Law, C.S., 2008: Predicting and monitoring the effects of large-scale ocean iron fertilization on marine trace gas emissions. *Marine Ecology Progress Series*, **364**, 283-288.

Law, C.S., E. Breitbarth, L.J. Hoffmann, C.M. McGraw, R.J. Langlois, J. LaRoche, A. Marriner, and K.A. Safi, 2012: No stimulation of nitrogen fixation by non-filamentous diazotrophs under elevated CO_2 in the South Pacific. *Global Change Biology*, **18(10)**, 3004-3014.

Le Borgne, R., V. Allain, S.P. Griffiths, R.J. Matear, A.D. McKinnon, A.J. Richardson, and J.W. Young, 2011: Vulnerability of oceanic food webs in the tropical Pacific to climate change. In: *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change* [Bell, J.D., J.E. Johnson, and A.J. Hobday (eds.)]. Secretariat of the Pacific Community, Noumea, New Caledonia, pp. 189-250.

Le Quesne, W.J.F. and J.K. Pinnegar, 2012: The potential impacts of ocean acidification: scaling from physiology to fisheries. *Fish and Fisheries*, **13(3)**, 333-344.

Leckie, R.M., T.J. Bralower, and R. Cashman, 2002: Oceanic anoxic events and planktonic evolution: biotic response to tectonic forcing during the mid-Cretaceous. *Paleoceanography*, **17(3)**, doi:10.1029/2001PA000623.

Leclercq, N., J.-P. Gattuso, and J. Jaubert, 2002: Primary production, respiration, and calcification of a coral reef mesocosm under increased CO_2 partial pressure. *Limnology and Oceanography*, **47(2)**, 558-564.

Lehodey, P., 2000: *Impacts of the El Niño Southern Oscillation on Tuna Populations and Fisheries in the Tropical Pacific Ocean*. SCTB 13 *W*orking Paper RG-1, 13th Meeting of Standing Committee on Tuna and Billfish (SCTB), Noumea, New Caledonia, 5-12 July 2000, Secretariat of the Pacific Community, Noumea, New Caledonia, 32 pp.

Lehodey, P., J. Hampton, R.W. Brill, S. Nicol, I. Senina, B. Calmetters, H.-O. Pörtner, L. Bopp, T. Llyina, J.D. Bell, and J. Sibert, 2011: Vulnerability of oceanic fisheries in the tropical Pacific to climate change. In: *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change* [Bell, J.D., J.E. Johnson, and A.J. Hobday (eds.)]. Secretariat of the Pacific Community, Noumea, New Caledonia, pp. 433-492.

Lenoir, S., G. Beaugrand, and É. Lecuyer, 2011: Modelled spatial distribution of marine fish and projected modifications in the North Atlantic Ocean. *Global Change Biology*, **17(1)**, 115-129.

Levin, L.A., 2003: Oxygen minimum zone benthos: adaptation and community response to hypoxia. *Oceanography and Marine Biology: an Annual Review*, **41**, 1-45.

Levin, L.A. and M. Sibuet, 2012: Understanding continental margin biodiversity: a new imperative. *Annual Review of Marine Science*, **4(1)**, 79-112.

Levin, L.A., W. Ekau, A.J. Gooday, F. Jorissen, J.J. Middelburg, S.W.A. Naqvi, C. Neira, N.N. Rabalais, and J. Zhang, 2009: Effects of natural and human-induced hypoxia on coastal benthos. *Biogeosciences*, **6(10)**, 2063-2098.

Levitan, O., G. Rosenberg, I. Setlik, E. Setlikova, J. Grigel, J. Klepetar, O. Prášil, and I. Berman-Frank, 2007: Elevated CO_2 enhances nitrogen fixation and growth in the marine cyanobacterium *Trichodesmium*. *Global Change Biology*, **13(2)**, 531-538.

Levitan, O., S.A. Kranz, D. Spungin, O. Prášil, B. Rost, and I. Berman-Frank, 2010: Combined effects of CO_2 and light on the N_2-fixing cyanobacterium *Trichodesmium* IMS101: a mechanistic view. *Plant Physiology*, **154(1)**, 346-356.

Lewandowska, A. and U. Sommer, 2010: Climate change and the spring bloom: a mesocosm study on the influence of light and temperature on phytoplankton and mesozooplankton. *Marine Ecology Progress Series*, **405**, 101-111.

Lewis, P.N., M.J. Riddle, and C.L. Hewitt, 2004: Management of exogenous threats to Antarctica and the sub-Antarctic islands: balancing risks from TBT and non-indigenous marine organisms. *Marine Pollution Bulletin*, **49(11-12)**, 999-1005.

Liggett, D., A. McIntosh, A. Thompson, N. Gilbert, and B. Storey, 2011: From frozen continent to tourism hotspot? Five decades of Antarctic tourism development and management, and a glimpse into the future. *Tourism Management*, **32(2)**, 357-366.

Lima, F.P., P.A. Ribeiro, N. Queiroz, S.J. Hawkins, and A.M. Santos, 2007: Do distributional shifts of northern and southern species of algae match the warming pattern? *Global Change Biology*, **13(12)**, 2592-2604.

Lindegren, M., C. Möllmann, A. Nielsen, K. Brander, B.R. MacKenzie, and N.C. Stenseth, 2010: Ecological forecasting under climate change: the case of Baltic cod. *Proceedings of the Royal Society B*, **277(1691)**, 2121-2130.

Lindenmayer, D.B., G.E. Likens, C.J. Krebs, and R.J. Hobbs, 2010: Improved probability of detection of ecological "surprises". *Proceedings of the National Academy of Sciences of the United States of America*, **107(51)**, 21957-21962.

Lindley, J.A., G. Beaugrand, C. Luczak, J.M. Dewarumez, and R.R. Kirby, 2010: Warm-water decapods and the trophic amplification of climate in the North Sea. *Biology Letters*, **6(6)**, 773-776.

Lipp, E.K., A. Huq, and R.R. Colwell, 2002: Effects of global climate on infectious disease: the cholera model. *Clinical Microbiology Reviews*, **15(4)**, 757-770.

Lischka, S., J. Büdenbender, T. Boxhammer, and U. Riebesell, 2011: Impact of ocean acidification and elevated temperatures on early juveniles of the polar shelled pteropod *Limacina helicina*: mortality, shell degradation, and shell growth. *Biogeosciences*, **8(4)**, 919-932.

Liu, J., M.G. Weinbauer, C. Maier, M.H. Dai, and J.-P. Gattuso, 2010: Effect of ocean acidification on microbial diversity and on microbe-driven biogeochemistry and ecosystem functioning. *Aquatic Microbial Ecology*, **61(3)**, 291-305.

Liu, W. and M. He, 2012: Effects of ocean acidification on the metabolic rates of three species of bivalve from southern coast of China. *Chinese Journal of Oceanology and Limnology*, **30(2)**, 206-211.

Llewellyn, L.E., 2010: Revisiting the association between sea surface temperature and the epidemiology of fish poisoning in the South Pacific: reassessing the link between ciguatera and climate change. *Toxicon*, **56(5)**, 691-697.

Lloret, J. and H.-J. Rätz, 2000: Condition of cod (*Gadus morhua*) off Greenland during 1982-1998. *Fisheries Research*, **48(1)**, 79-86.

Lobitz, B., L. Beck, A. Huq, B. Wood, G. Fuchs, A.S.G. Faruque, and R. Colwell, 2000: Climate and infectious disease: use of remote sensing for detection of *Vibrio cholerae* by indirect measurement. *Proceedings of the National Academy of Sciences of the United States of America*, **97(4)**, 1438-1443.

Lohbeck, K.T., U. Riebesell, and T.B.H. Reusch, 2012: Adaptive evolution of a key phytoplankton species to ocean acidification. *Nature Geoscience*, **5(5)**, 346-351.

Lomas, M.W., B.M. Hopkinson, J.L. Losh, D.E. Ryan, D.L. Shi, Y. Xu, and F.M.M. Morel, 2012: Effect of ocean acidification on cyanobacteria in the subtropical North Atlantic. *Aquatic Microbial Ecology*, **66(3)**, 211-222.

Lombard, F., R.E. da Rocha, J. Bijma, and J.-P. Gattuso, 2010: Effect of carbonate ion concentration and irradiance on calcification in planktonic foraminifera. *Biogeosciences*, **7(1)**, 247-255.

Lovelock, J.E. and C.G. Rapley, 2007: Ocean pipes could help the Earth to cure itself. *Nature*, **449(7161)**, 403.

Loya, Y., K. Sakai, K. Yamazato, Y. Nakano, H. Sambali, and R. van Woesik, 2001: Coral bleaching: the winners and the losers. *Ecology Letters*, **4(2)**, 122-131.

Luczak, C., G. Beaugrand, M. Jaffré, and S. Lenoir, 2011: Climate change impact on Balearic shearwater through a trophic cascade. *Biology Letters*, **7(5)**, 702-705.

Maas, A.E., K.F. Wishner, and B.A. Seibel, 2012: The metabolic response of pteropods to ocean acidification reflects natural CO_2-exposure in oxygen minimum zones. *Biogeosciences*, **9(2)**, 747-757.

Mackas, D.L., 2011: Does blending of chlorophyll data bias temporal trend? *Nature*, **472(7342)**, E4-E5.

Mackas, D.L., R.H. Goldblatt, and A.G. Lewis, 1998: Interdecadal variation in developmental timing of *Neocalanus plumchrus* populations at Ocean Station P in the subarctic North Pacific. *Canadian Journal of Fisheries and Aquatic Sciences*, **55(8)**, 1878-1893.

MacLeod, C.D., 2009: Global climate change, range changes and potential implications for the conservation of marine cetaceans: a review and synthesis. *Endangered Species Research*, **7**, 125-136.

MacLeod, C.D., S.M. Bannon, G.J. Pierce, C. Schweder, J.A. Learmonth, J.S. Herman, and R.J. Reid, 2005: Climate change and the cetacean community of north-west Scotland. *Biological Conservation*, **124(4)**, 477-483.

Maier, C., J. Hegeman, M.G. Weinbauer, and J.-P. Gattuso, 2009: Calcification of the cold-water coral *Lophelia pertusa* under ambient and reduced pH. *Biogeosciences*, **6(8)**, 1671-1680.

Maier, C., A. Schubert, M.M. Berzunza Sànchez, M.G. Weinbauer, P. Watremez, and J.-P. Gattuso, 2013: End of the century pCO_2 levels do not impact calcification in Mediterranean cold-water corals. *PLoS ONE*, **8(4)**, e62655, doi:10.1371/journal.pone.0062655.

Manzello, D.P., J.A. Kleypas, D.A. Budd, C.M. Eakin, P.W. Glynn, and C. Langdon, 2008: Poorly cemented coral reefs of the eastern tropical Pacific: possible insights into reef development in a high-CO_2 world. *Proceedings of the National Academy of Sciences of the United States of America*, **105(30)**, 10450-10455.

Marañón, E., P. Cermeño, M. Latasa, and R.D. Tadonléké, 2012: Temperature, resources, and phytoplankton size structure in the ocean. *Limnology and Oceanography*, **57(5)**, 1266-1278.

Marbà, N. and C.M. Duarte, 2010: Mediterranean warming triggers seagrass (*Posidonia oceanica*) shoot mortality. *Global Change Biology*, **16(8)**, 2366-2375.

Margalef, R., 1978: Life-forms of phytoplankton as survival alternatives in an unstable environment. *Oceanologica Acta*, **1(4)**, 493-509.

MARGO Project Members, 2009: Constraints on the magnitude and patterns of ocean cooling at the Last Glacial Maximum. *Nature Geoscience*, **2(2)**, 127-132.

Mark, F.C., C. Bock, and H.-O. Pörtner, 2002: Oxygen-limited thermal tolerance in Antarctic fish investigated by MRI and ^{31}P-MRS. *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology*, **283(5)**, R1254-1262.

Martin, S. and J.-P. Gattuso, 2009: Response of Mediterranean coralline algae to ocean acidification and elevated temperature. *Global Change Biology*, **15(8)**, 2089-2100.

Martin, S., R. Rodolfo-Metalpa, E. Ransome, S. Rowley, M.C. Buia, J.-P. Gattuso, and J. Hall-Spencer, 2008: Effects of naturally acidified seawater on seagrass calcareous epibionts. *Biology Letters*, **4(6)**, 689-692.

Martin, S., S. Richier, M.-L. Pedrotti, S. Dupont, C. Castejon, Y. Gerakis, M.-E. Kerros, F. Oberhänsli, J.-L. Teyssié, R. Jeffree, and J.-P. Gattuso, 2011: Early development and molecular plasticity in the Mediterranean sea urchin *Paracentrotus lividus* exposed to CO_2-driven acidification. *Journal of Experimental Biology*, **214(8)**, 1357-1368.

Martrat, B., J.O. Grimalt, C. Lopez-Martinez, I. Cacho, F.J. Sierro, J.A. Flores, R. Zahn, M. Canals, J.H. Curtis, and D.A. Hodell, 2004: Abrupt temperature changes in the Western Mediterranean over the past 250,000 years. *Science*, **306(5702)**, 1762-1765.

Matear, R.J. and A.C. Hirst, 1999: Climate change feedback on the future oceanic CO_2 uptake. *Tellus Series B: Chemical and Physical Meteorology*, **51(3)**, 722-733.

Mazaris, A.D., A.S. Kallimanis, S.P. Sgardelis, and J.D. Pantis, 2008: Do long-term changes in sea surface temperature at the breeding areas affect the breeding dates and reproduction performance of Mediterranean loggerhead turtles? Implications for climate change. *Journal of Experimental Marine Biology and Ecology*, **367(2)**, 219-226.

Mazaris, A.D., A.S. Kallimanis, J. Tzanopoulos, S.P. Sgardelis, and J.D. Pantis, 2009: Sea surface temperature variations in core foraging grounds drive nesting trends and phenology of loggerhead turtles in the Mediterranean Sea. *Journal of Experimental Marine Biology and Ecology*, **379(1-2)**, 23-27.

McBryan, T.L., K. Anttila, T.M. Healy, and P.M. Schulte, 2013: Responses to temperature and hypoxia as interacting stressors in fish: implications for adaptation to environmental change. *Integrative and Comparative Biology*, **53(4)**, 648-659.

McClain, C.R., 2009: A decade of satellite ocean color observations. *Annual Review of Marine Science*, **1(1)**, 19-42.

McClatchie, S., R. Goericke, R. Cosgrove, G. Auad, and R. Vetter, 2010: Oxygen in the Southern California Bight: multidecadal trends and implications for demersal fisheries. *Geophysical Research Letters*, **37**, L19602, doi:10.1029/2010GL044497.

McCulloch, M., J. Falter, J. Trotter, and P. Montagna, 2012: Coral resilience to ocean acidification and global warming through pH up-regulation. *Nature Climate Change*, **2(8)**, 623-627.

McDaniel, L.D., E. Young, J. Delaney, F. Ruhnau, K.B. Ritchie, and J.H. Paul, 2010: High frequency of horizontal gene transfer in the oceans. *Science*, **330(6000)**, 50.

McIntyre, T., I.J. Ansorge, H. Bornemann, J. Plötz, C.A. Tosh, and M.N. Bester, 2011: Elephant seal dive behaviour is influenced by ocean temperature: implications for climate change impacts on an ocean predator. *Marine Ecology Progress Series*, **441**, 257-272.

McLeod, E., K.R.N. Anthony, A. Andersson, R. Beeden, Y. Golbuu, J. Kleypas, K. Kroeker, D. Manzello, R.V. Salm, H. Schuttenberg, and J.E. Smith, 2013: Preparing to manage coral reefs for ocean acidification: lessons from coral bleaching. *Frontiers in Ecology and the Environment*, **11(1)**, 20-27.

McMahon, C.R. and G.C. Hays, 2006: Thermal niche, large-scale movements and implications of climate change for a critically endangered marine vertebrate. *Global Change Biology*, **12(7)**, 1330-1338.

McQuatters-Gollop, A., P.C. Reid, M. Edwards, P.H. Burkill, C. Castellani, S. Batten, W. Gieskes, D. Beare, R.R. Bidigare, E. Head, R. Johnson, M. Kahru, J.A. Koslow, and A. Pena, 2011: Is there a decline in marine phytoplankton? *Nature*, **472(7342)**, E6-E7.

Meinshausen, M., S.J. Smith, K. Calvin, J.S. Daniel, M.L.T. Kainuma, J.F. Lamarque, K. Matsumoto, S.A. Montzka, S.C.B. Raper, K. Riahi, A. Thomson, G.J.M. Velders, and D.P.P. van Vuuren, 2011: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change*, **109(1-2)**, 213-241.

Meissner, K.J., T. Lippmann, and A. Sen Gupta, 2012: Large-scale stress factors affecting coral reefs: open ocean sea surface temperature and surface seawater aragonite saturation over the next 400 years. *Coral Reefs*, **31(2)**, 309-319.

Melzner, F., S. Göbel, M. Langenbuch, M.A. Gutowska, H.-O. Pörtner, and M. Lucassen, 2009: Swimming performance in Atlantic Cod (*Gadus morhua*) following long-term (4-12 months) acclimation to elevated seawater P(CO_2). *Aquatic Toxicology*, **92(1)**, 30-37.

Melzner, F., P. Stange, K. Trubenbach, J. Thomsen, I. Casties, U. Panknin, S.N. Gorb, and M.A. Gutowska, 2011: Food supply and seawater pCO_2 impact calcification and internal shell dissolution in the blue mussel *Mytilus edulis*. *PLoS ONE*, **6(9)**, e24223, doi:10.1371/journal.pone.0024223.

Merico, A., T. Tyrrell, E.J. Lessard, T. Oguz, P.J. Stabeno, S.I. Zeeman, and T.E. Whitledge, 2004: Modelling phytoplankton succession on the Bering Sea shelf: role of climate influences and trophic interactions in generating *Emiliania huxleyi* blooms 1997-2000. *Deep-Sea Research Part I: Oceanographic Research Papers*, **51(12)**, 1803-1826.

Metzger, R.A. and G. Benford, 2001: Sequestering of atmospheric carbon through permanent disposal of crop residue. *Climatic Change*, **49(1-2)**, 11-19.

Michaelidis, B., C. Ouzounis, A. Paleras, and H.-O. Pörtner, 2005: Effects of long-term moderate hypercapnia on acid-base balance and growth rate in marine mussels *Mytilus galloprovincialis*. *Marine Ecology Progress Series*, **293**, 109-118.

Milazzo, M., S. Mirto, P. Domenici, and M. Gristina, 2013: Climate change exacerbates interspecific interactions in sympatric coastal fishes. *Journal of Animal Ecology*, **82(2)**, 468-477.

Miller, A.W., A.C. Reynolds, C. Sobrino, and G.F. Riedel, 2009: Shellfish face uncertain future in high CO_2 world: influence of acidification on oyster larvae calcification and growth in estuaries. *PLoS ONE*, **4(5)**, e5661, doi:10.1371/journal.pone.0005661.

Millero, F.J., 1995: Thermodynamics of the carbon dioxide system in the oceans. *Geochimica et Cosmochimica Acta*, **59(4)**, 661-677.

Mills, C.E., 2001: Jellyfish blooms: are populations increasing globally in response to changing ocean conditions? *Hydrobiologia*, **451**, 55-68.

Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer, 2008: Stationarity is dead: whither water management? *Science*, **319(5863)**, 573-574.

Molinero, J.B., F. Ibanez, P. Nival, E. Buecher, and S. Souissi, 2005: North Atlantic climate and northwestern Mediterranean plankton variability. *Limnology and Oceanography*, **50(4)**, 1213-1220.

Moloney, C.L., M.A. St. John, K.L. Denman, D.M. Karl, F.W. Köster, S. Sundby, and R.P. Wilson, 2011: Weaving marine food webs from end to end under global change. *Journal of Marine Systems*, **84(3-4)**, 106-116.

Moore, J.K., S.C. Doney, D.M. Glover, and I.Y. Fung, 2002: Iron cycling and nutrient-limitation patterns in surface waters of the World Ocean. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **49(1-3)**, 463-507.

Moore, S.E. and H.P. Huntington, 2008: Arctic marine mammals and climate change: impacts and resilience. *Ecological Applications*, **18(2)**, S157-S165.

Moore, W.R., 2010: The impact of climate change on Caribbean tourism demand. *Current Issues in Tourism*, **13(5)**, 495-505.

Mora, C., C.-L. Wei, A. Rollo, T. Amaro, A.R. Baco, D. Billett, L. Bopp, Q. Chen, M. Collier, R. Danovaro, A.J. Gooday, B.M. Grupe, P.R. Halloran, J. Ingels, D.O.B. Jones, L.A. Levin, H. Nakano, K. Norling, E. Ramirez-Llodra, M. Rex, H.A. Ruhl, C.R. Smith, A.K. Sweetman, A.R. Thurber, J.F. Tjiputra, P. Usseglio, L. Watling, T. Wu, and M. Yasuhara, 2013: Biotic and human vulnerability to projected changes in ocean biogeochemistry over the 21st century. *PLoS Biology*, **11(10)**, e1001682, doi:10.1371/journal.pbio.1001682.

Morán, X.A.G., Á. López-Urrutia, A. Calvo-Díaz, and W.K.W. Li, 2010: Increasing importance of small phytoplankton in a warmer ocean. *Global Change Biology*, **16(3)**, 1137-1144.

Moss, R.H., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren, T.R. Carter, S. Emori, M. Kainuma, T. Kram, G.A. Meehl, J.F.B. Mitchell, N. Nakićenović, K. Riahi, S.J. Smith, R.J. Stouffer, A.M. Thomson, J.P. Weyant, and T.J. Wilbanks, 2010: The next generation of scenarios for climate change research and assessment. *Nature*, **463(7282)**, 747-756.

Mountain, D.G. and J. Kane, 2010: Major changes in the Georges Bank ecosystem, 1980s to the 1990s. *Marine Ecology Progress Series*, **398**, 81-91.

Mouriño-Carballido, B., R. Graña, A. Fernández, A. Bode, M. Varela, J.F. Domínguez, J. Escánez, D. de Armas, and E. Marañón, 2011: Importance of N_2 fixation vs. nitrate eddy diffusion along a latitudinal transect in the Atlantic Ocean. *Limnology and Oceanography*, **56(3)**, 999-1007.

Moy, A.D., W.R. Howard, S.G. Bray, and T.W. Trull, 2009: Reduced calcification in modern Southern Ocean planktonic foraminifera. *Nature Geoscience*, **2(4)**, 276-280.

Moya, A., L. Huisman, E.E. Ball, D.C. Hayward, L.C. Grasso, C.M. Chua, H.N. Woo, J.-P. Gattuso, S. Forêt, and D.J. Miller, 2012: Whole transcriptome analysis of the coral *Acropora millepora* reveals complex responses to CO_2-driven acidification during the initiation of calcification. *Molecular Ecology*, **21(10)**, 2440-2454.

Müller, R., T. Laepple, I. Bartsch, and C. Wiencke, 2009: Impact of oceanic warming on the distribution of seaweeds in polar and cold-temperate waters. *Botanica Marina*, **52(6)**, 617-638.

Munday, P.L., J.M. Donelson, D.L. Dixson, and G.G. Endo, 2009a: Effects of ocean acidification on the early life history of a tropical marine fish. *Proceedings of the Royal Society B*, **276(1671)**, 3275-3283.

Munday, P.L., N.E. Crawley, and G.E. Nilsson, 2009b: Interacting effects of elevated temperature and ocean acidification on the aerobic performance of coral reef fishes. *Marine Ecology Progress Series*, **388**, 235-242.

Munday, P.L., D.L. Dixson, M.I. McCormick, M. Meekan, M.C.O. Ferrari, and D.P. Chivers, 2010: Replenishment of fish populations is threatened by ocean acidification. *Proceedings of the National Academy of Sciences of the United States of America*, **107(29)**, 12930-12934.

Munday, P.L., M. Gagliano, J.M. Donelson, D.L. Dixson, and S.R. Thorrold, 2011a: Ocean acidification does not affect the early life history development of a tropical marine fish. *Marine Ecology Progress Series*, **423**, 211-221.

Munday, P.L., V. Hernaman, D.L. Dixson, and S.R. Thorrold, 2011b: Effect of ocean acidification on otolith development in larvae of a tropical marine fish. *Biogeosciences*, **8(2)**, 1631-1641.

Naqvi, S.W.A., D.A. Jayakumar, P.V. Narvekar, H. Naik, V.V.S.S. Sarma, W. D'Souza, S. Joseph, and M.D. George, 2000: Increased marine production of N_2O due to intensifying anoxia on the Indian continental shelf. *Nature*, **408(6810)**, 346-349.

Narita, D., K. Rehdanz, and R.S.J. Tol, 2012: Economic costs of ocean acidification: a look into the impacts on global shellfish production. *Climatic Change*, **113(3-4)**, 1049-1063.

Navarro, J.M., R. Torres, K. Acuña, C. Duarte, P.H. Manriquez, M. Lardies, N.A. Lagos, C. Vargas, and V. Aguilera, 2013: Impact of medium-term exposure to elevated pCO_2 levels on the physiological energetics of the mussel *Mytilus chilensis*. *Chemosphere*, **90(3)**, 1242-1248.

Neuheimer, A.B. and P. Grønkjær, 2012: Climate effects on size-at-age: growth in warming waters compensates for earlier maturity in an exploited marine fish. *Global Change Biology*, **18(6)**, 1812-1822.

Neuheimer, A.B., R.E. Thresher, J.M. Lyle, and J.M. Semmens, 2011: Tolerance limit for fish growth exceeded by warming waters. *Nature Climate Change*, **1(2)**, 110-113.

Neutel, A.M., J.A.P. Heesterbeek, J. van de Koppel, G. Hoenderboom, A. Vos, C. Kaldeway, F. Berendse, and P.C. de Ruiter, 2007: Reconciling complexity with stability in naturally assembling food webs. *Nature*, **449**, 599-602.

Nilsson, G.E., N. Crawley, I.G. Lunde, and P.L. Munday, 2009: Elevated temperature reduces the respiratory scope of coral reef fishes. *Global Change Biology*, **15(6)**, 1405-1412.

Nilsson, G.E., S. Östlund-Nilsson, and P.L. Munday, 2010: Effects of elevated temperature on coral reef fishes: loss of hypoxia tolerance and inability to acclimate. *Comparative Biochemistry and Physiology A: Molecular and Integrative Physiology*, **156(4)**, 389-393.

Nilsson, G.E., D.L. Dixson, P. Domenici, M.I. McCormick, C. Sørensen, S.-A. Watson, and P.L. Munday, 2012: Near-future carbon dioxide levels alter fish behaviour by interfering with neurotransmitter function. *Nature Climate Change*, **2(3)**, 201-204.

NOAA, 2012: *NOAA Extended Reconstructed Sea Surface Temperature (SST) Version 3b*. From: PSD Climate and Weather Data, NOAA/OAR/ESRL Physical Sciences Division, Boulder, CO, USA, www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.html.

Nuttall, M., 1998: *Protecting the Arctic: Indigenous Peoples and Cultural Survival*. Routledge, London, 195 pp.

O'Connor, M.I., M.F. Piehler, D.M. Leech, A. Anton, and J.F. Bruno, 2009: Warming and resource availability shift food web structure and metabolism. *PLoS Biology*, **7(8)**, e1000178, doi:10.1371/journal.pbio.1000178.

O'Donnell, M.J., A.E. Todgham, M.A. Sewell, L.M. Hammond, K. Ruggiero, N.A. Fangue, M.L. Zippay, and G.E. Hofmann, 2010: Ocean acidification alters skeletogenesis and gene expression in larval sea urchins. *Marine Ecology Progress Series*, **398**, 157-171.

Occhipinti-Ambrogi, A., 2007: Global change and marine communities: alien species and climate change. *Marine Pollution Bulletin*, **55(7-9)**, 342-352.

Ohman, M.D., B.E. Lavaniegos, and A.W. Townsend, 2009: Multi-decadal variations in calcareous holozooplankton in the California Current System: thecosome pteropods, heteropods, and foraminifera. *Geophysical Research Letters*, **36**, L18608, doi:10.1029/2009GL039901.

Olafsson, J., S.R. Olafsdottir, A. Benoit-Cattin, M. Danielsen, T.S. Arnarson, and T. Takahashi, 2009: Rate of Iceland Sea acidification from time series measurements. *Biogeosciences*, **6(11)**, 2661-2668.

Orr, J.C., V.J. Fabry, O. Aumont, L. Bopp, S.C. Doney, R.A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, R.M. Key, K. Lindsay, E. Maier-Reimer, R. Matear, P. Monfray, A. Mouchet, R.G. Najjar, G.-K. Plattner, K.B. Rodgers, C.L. Sabine, J.L. Sarmiento, R. Schlitzer, R.D. Slater, I.J. Totterdell, M.-F. Weirig, Y. Yamanaka, and A. Yool, 2005: Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, **437(7059)**, 681-686.

Oschlies, A., M. Pahlow, A. Yool, and R.J. Matear, 2010: Climate engineering by artificial ocean upwelling: channelling the sorcerer's apprentice. *Geophysical Research Letters*, **37**, L04701, doi:10.1029/2009GL041961.

Österblom, H., S. Hansson, U. Larsson, O. Hjerne, F. Wulff, R. Elmgren, and C. Folke, 2007: Human-induced trophic cascades and ecological regime shifts in the Baltic Sea. *Ecosystems*, **10(6)**, 877-889.

Ottersen, G., D.O. Hjermann, and N.C. Stenseth, 2006: Changes in spawning stock structure strengthen the link between climate and recruitment in a heavily fished cod (*Gadus morhua*) stock. *Fisheries Oceanography*, **15(3)**, 230-243.

Ottersen, G., S. Kim, G. Huse, J.J. Polovina, and N.C. Stenseth, 2010: Major pathways by which climate may force marine fish populations. *Journal of Marine Systems*, **79(3-4)**, 343-360.

Pagani, M., Z. Liu, J. LaRiviere, and A.C. Ravelo, 2010: High Earth-system climate sensitivity determined from Pliocene carbon dioxide concentrations. *Nature Geoscience*, **3(1)**, 27-30.

Pakker, H., A.M. Breeman, W.F.P. van Reine, and C. van den Hoek, 1995: A comparative study of temperature responses of Carribean seaweeds from different biogeographic groups. *Journal of Phycology*, **31(4)**, 499-507.

Palacios, S.L. and R.C. Zimmerman, 2007: Response of eelgrass *Zostera marina* to CO_2 enrichment: possible impacts of climate change and potential for remediation of coastal habitats. *Marine Ecology Progress Series*, **344**, 1-13.

Pancost, R.D., N. Crawford, S. Magness, A. Turner, H.C. Jenkyns, and J.R. Maxwell, 2004: Further evidence for the development of photic-zone euxinic conditions during Mesozoic oceanic anoxic events. *Journal of the Geological Society*, **161**, 353-364.

Pane, E.F. and J.P. Barry, 2007: Extracellular acid-base regulation during short-term hypercapnia is effective in a shallow-water crab, but ineffective in a deep-sea crab. *Marine Ecology Progress Series*, **334**, 1-9.

Parker, L.M., P.M. Ross, and W.A. O'Connor, 2011: Populations of the Sydney rock oyster, *Saccostrea glomerata*, vary in response to ocean acidification. *Marine Biology*, **158(3)**, 689-697.

Parker, L.M., P.M. Ross, W.A. O'Connor, L. Borysko, D.A. Raftos, and H.-O. Pörtner, 2012: Adult exposure influences offspring response to ocean acidification in oysters. *Global Change Biology*, **18(1)**, 82-92.

Parmesan, C. and J. Matthews, 2005: Biological impacts of climate change. In: *Principles of Conservation Biology* [Groom, M.J., G.K. Meffe, and C.R. Carroll (eds.)]. Sinauer, Sunderland, MA, pp. 333-374.

Parmesan, C., C. Duarte, E. Poloczanska, A.J. Richardson, and M.C. Singer, 2011: Overstretching attribution. *Nature Climate Change*, **1(1)**, 2-4.

Parsons, L.S. and W.H. Lear, 2001: Climate variability and marine ecosystem impacts: a North Atlantic perspective. *Progress in Oceanography*, **49(1-4)**, 167-188.

Pascual, M., X. Rodo, S.P. Ellner, R. Colwell, and M.J. Bouma, 2000: Cholera dynamics and El Niño-Southern Oscillation. *Science*, **289(5485)**, 1766-1769.

Paulmier, A. and D. Ruiz-Pino, 2009: Oxygen minimum zones (OMZs) in the modern ocean. *Progress in Oceanography*, **80(3-4)**, 113-128.

Paulmier, A., D. Ruiz-Pino, and V. Garçon, 2011: CO_2 maximum in the oxygen minimum zone (OMZ). *Biogeosciences*, **8(2)**, 239-252.

Pauly, D., V. Christensen, J. Dalsgaard, R. Froese, and F. Torres Jr., 1998: Fishing down marine food webs. *Science*, **279(5352)**, 860-863.

Peck, L.S., S.A. Morley and M.S. Clark, 2010: Poor acclimation capacities in Antarctic marine ectotherms. *Marine Biology*, **157(9)**, 2051-2059.

Péron, C., H. Weimerskirch, and C.-A. Bost, 2012: Projected poleward shift of king penguins' (*Aptenodytes patagonicus*) foraging range at the Crozet Islands, southern Indian Ocean. *Proceedings of the Royal Society B: Biological Sciences*, **279(1738)**, 2515-2523.

Perry, A.L., P.J. Low, J.R. Ellis, and J.D. Reynolds, 2005: Climate change and distribution shifts in marine fishes. *Science*, **308(5730)**, 1912-1915.

Perry, R.I., P. Cury, K. Brander, S. Jennings, C. Möllmann, and B. Planque, 2010: Sensitivity of marine systems to climate and fishing: concepts, issues and management responses. *Journal of Marine Systems*, **79(3-4)**, 427-435.

Pershing, A.J., C.H. Greene, J.W. Jossi, L. O'Brien, J.K.T. Brodziak, and B.A. Bailey, 2005: Interdecadal variability in the Gulf of Maine zooplankton community, with potential impacts on fish recruitment. *ICES Journal of Marine Science*, **62(7)**, 1511-1523.

Pershing, A.J., E.H.J. Head, C.H. Greene, and J.W. Jossi, 2010: Pattern and scale of variability among Northwest Atlantic Shelf plankton communities. *Journal of Plankton Research*, **32(12)**, 1661-1674.

Pespeni, M.H., E. Sanford, B. Gaylord, T.M. Hill, J.D. Hosfelt, H.K. Jaris, M. LaVigne, E.A. Lenz, A.D. Russell, M.K. Young, and S.R. Palumbi, 2013: Evolutionary change during experimental ocean acidification. *Proceedings of the National Academy of Sciences of the United States of America*, **110(17)**, 6937-6942.

Petitgas, P., D. Reid, B. Planque, E. Nogueira, B. O'Hea, and U. Cotano, 2006: The entrainment hypothesis: an explanation for the persistance and innovation in spawning migrations and life cycle spatial patterns. In: *International Council for the Exploration of the Sea (ICES) Conference and Meeting Documents (CM) 2006* [ICES (ed.)]. ICES CM 2006/B07, ICES, Maastricht, Netherlands, 9 pp.

Philippart, C.J.M., R. Anadón, R. Danovaro, J.W. Dippner, K.F. Drinkwater, S.J. Hawkins, T. Oguz, G. O'Sullivan, and P.C. Reid, 2011: Impacts of climate change on European marine ecosystems: observations, expectations and indicators. *Journal of Experimental Marine Biology and Ecology*, **400(1-2)**, 52-69.

Pierce, D.W., P.J. Gleckler, T.P. Barnett, B.D. Santer, and P.J. Durack, 2012: The fingerprint of human-induced changes in the ocean's salinity and temperature fields. *Geophysical Research Letters*, **39(21)**, L21704, doi:10.1029/2012GL053389.

Pike, D.A., R.L. Antworth, and J.C. Stiner, 2006: Earlier nesting contributes to shorter nesting seasons for the loggerhead seaturtle, *Caretta caretta*. *Journal of Herpetology*, **40(1)**, 91-94.

Pinsky, M.L. and M. Fogarty, 2012: Lagged social-ecological responses to climate and range shifts in fisheries. *Climatic Change*, **115(3-4)**, 883-891.

Pinsky, M.L., B. Worm, M.J. Fogarty, J.L. Sarmiento, and S.A. Levin, 2013: Marine taxa track local climate velocities. *Science*, **341(6151)**, 1239-1242.

Piontek, J., M. Lunau, N. Händel, C. Borchard, M. Wurst, and A. Engel, 2010: Acidification increases microbial polysaccharide degradation in the ocean. *Biogeosciences*, **7(5)**, 1615-1624.

Pitchford, J.W. and J. Brindley, 1999: Iron limitation, grazing pressure and oceanic high nutrient-low chlorophyll (HNLC) regions. *Journal of Plankton Research*, **21(3)**, 525-547.

Planque, B., J.-M. Fromentin, P. Cury, K.F. Drinkwater, S. Jennings, R.I. Perry, and S. Kifani, 2010: How does fishing alter marine populations and ecosystems sensitivity to climate? *Journal of Marine Systems*, **79(3-4)**, 403-417.

Planque, B., E. Bellier, and C. Loots, 2011a: Uncertainties in projecting spatial distributions of marine populations. *ICES Journal of Marine Science*, **68(6)**, 1045-1050.

Planque, B., C. Loots, P. Petitgas, U. Lindstrøm, and S. Vaz, 2011b: Understanding what controls the spatial distribution of fish populations using a multi-model approach. *Fisheries Oceanography*, **20(1)**, 1-17.

Poloczanska, E.S., S.J. Hawkins, A.J. Southward, and M.T. Burrows, 2008: Modeling the response of populations of competing species to climate change. *Ecology*, **89(11)**, 3138-3149.

Poloczanska, E.S., C.J. Brown, W.J. Sydeman, W. Kiessling, D.S. Schoeman, P.J. Moore, K. Brander, J.F. Bruno, L.B. Buckley, M.T. Burrows, C.M. Duarte, B.S. Halpern, J. Holding, C.V. Kappel, M.I. O'Connor, J.M. Pandolfi, C. Parmesan, F. Schwing, S.A. Thompson, and A.J. Richardson, 2013: Global imprint of climate change on marine life. *Nature Climate Change*, **3(10)**, 919-925.

Polovina, J.J., E.A. Howell, and M. Abecassis, 2008: Ocean's least productive waters are expanding. *Geophysical Research Letters*, **35(3)**, L03618, doi:10.1029/2007GL031745.

Polovina, J.J., J.P. Dunne, P.A. Woodworth, and E.A. Howell, 2011: Projected expansion of the subtropical biome and contraction of the temperate and equatorial upwelling biomes in the North Pacific under global warming. *ICES Journal of Marine Science*, **68(6)**, 986-995.

Pörtner, H.-O., 2002a: Climate variations and the physiological basis of temperature dependent biogeography: systemic to molecular hierarchy of thermal tolerance in animals. *Comparative Biochemistry and Physiology A: Molecular and Integrative Physiology*, **132(4)**, 739-761.

Pörtner, H.-O., 2002b: Environmental and functional limits to muscular exercise and body size in marine invertebrate athletes. *Comparative Biochemistry and Physiology A: Molecular and Integrative Physiology*, **133(2)**, 303-321.

Pörtner, H.-O., 2006: Climate-dependent evolution of Antarctic ectotherms: an integrative analysis. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **53(8-10)**, 1071-1104.

Pörtner, H.-O., 2008: Ecosystem effects of ocean acidification in times of ocean warming: a physiologist's view. *Marine Ecology Progress Series*, **373**, 203-217.

Pörtner, H.-O., 2010: Oxygen- and capacity-limitation of thermal tolerance: a matrix for integrating climate-related stressor effects in marine ecosystems. *Journal of Experimental Biology*, **213(6)**, 881-893.

Pörtner, H.-O., 2012: Integrating climate-related stressor effects on marine organisms: unifying principles linking molecule to ecosystem-level changes. *Marine Ecology Progress Series*, **470**, 273-290.

Pörtner, H.-O. and A.P. Farrell, 2008: Ecology: physiology and climate change. *Science*, **322(5902)**, 690-692.

Pörtner, H.-O. and M.K. Grieshaber, 1993: Critical Po_2(s) in oxyconforming and oxyregulating animals: gas exchange, metabolic rate and the mode of energy production. In: *The Vertebrate Gas Transport Cascade: Adaptations to Environment and Mode of Life* [Bicudo, J.E.P.W. (ed.)]. CRC Press Inc, Boca Raton, FL, USA, pp. 330-357.

Pörtner, H.-O. and R. Knust, 2007: Climate change affects marine fishes through the oxygen limitation of thermal tolerance. *Science*, **315(5808)**, 95-97.

Pörtner, H.-O. and M.A. Peck, 2010: Climate change effects on fishes and fisheries: towards a cause-and-effect understanding. *Journal of Fish Biology*, **77(8)**, 1745-1779.

Pörtner, H.-O., A. Reipschläger, and N. Heisler, 1998: Acid-base regulation, metabolism and energetics in *Sipunculus nudus* as a function of ambient carbon dioxide level. *Journal of Experimental Biology*, **201(1)**, 43-55.

Pörtner, H.-O., C. Bock, and A. Reipschläger, 2000: Modulation of the cost of pHi regulation during metabolic depression: a ^{31}P-NMR study in invertebrate (*Sipunculus nudus*) isolated muscle. *Journal of Experimental Biology*, **203(16)**, 2417-2428.

Pörtner, H.-O., M. Langenbuch, and B. Michaelidis, 2005: Synergistic effects of temperature extremes, hypoxia, and increases in CO_2 on marine animals: from Earth history to global change. *Journal of Geophysical Research*, **110(C9)**, C09S10, doi:10.1029/2004JC002561.

Pörtner, H.-O., L.S. Peck, and T. Hirse, 2006: Hyperoxia alleviates thermal stress in the Antarctic bivalve, *Laternula elliptica*: evidence for oxygen limited thermal tolerance. *Polar Biology*, **29(8)**, 688-693.

Pörtner, H.-O., C. Bock, R. Knust, G. Lannig, M. Lucassen, F.C. Mark, and F.J. Sartoris, 2008: Cod and climate in a latitudinal cline: physiological analyses of climate effects in marine fishes. *Climate Research*, **37(2-3)**, 253-270.

Pörtner, H.-O., P.M. Schulte, C.M. Wood, and F. Schiemer, 2010: Niche dimensions in fishes: an integrative view. *Physiological and Biochemical Zoology*, **83(5)**, 808-826.

Pörtner, H.-O., M. Gutowska, A. Ishimatsu, M. Lucassen, F. Melzner, and B. Seibel, 2011: Effects of ocean acidification on nektonic organisms. In: *Ocean Acidification* [Gattuso, J.-P. and L. Hansson (eds.)]. Oxford University Press, Oxford, UK, pp. 154-175.

Pörtner, H.-O., L.S. Peck, and G.N. Somero, 2012: Mechanisms defining thermal limits and adaptation in marine ectotherms: integrative view. In: *Antarctic Ecosystems: An Extreme Environment in a Changing World* [Rogers, A., N.M. Johnston, E.J. Murphy, and A. Clarke (eds.)]. Wiley-Blackwell, Chichester, UK, pp. 360-396.

Porzio, L., M.C. Buia, and J.M. Hall-Spencer, 2011: Effects of ocean acidification on macroalgal communities. *Journal of Experimental Marine Biology and Ecology*, **400(1-2)**, 278-287.

Prince, E.D., J. Luo, C.P. Goodyear, J.P. Hoolihan, D. Snodgrass, E.S. Orbesen, J.E. Serafy, M. Ortiz, and M.J. Schirripa, 2010: Ocean scale hypoxia-based habitat compression of Atlantic istiophorid billfishes. *Fisheries Oceanography*, **19(6)**, 448-462.

Purcell, J.E. and M.B. Decker, 2005: Effects of climate on relative predation by scyphomedusae and ctenophores on copepods in Chesapeake Bay during 1987-2000. *Limnology and Oceanography*, **50(1)**, 376-387.

Quartino M.L., D. Deregibus, G,L, Campana, G.E.J. Latorre, and F.R. Momo, 2013: Evidence of macroalgal colonization on newly ice-free areas following glacial retreat in Potter Cove (South Shetland Islands), Antarctica. *PLoS ONE* **8(3)**, e58223. doi:10.1371/journal.pone.0058223.

Queste, B.Y., L. Fernand, T.D. Jickells, and K.J. Heywood, 2013: Spatial extent and historical context of North Sea oxygen depletion in August 2010. *Biogeochemistry*, **113(1-3)**, 53-68.

Raab, K., M. Llope, L.A.J. Nagelkerke, A.D. Rijnsdorp, L.R. Teal, P. Licandro, P. Ruardij, and M. Dickey-Collas, 2013: Influence of temperature and food availability on juvenile European anchovy *Engraulis encrasicolus* at its northern boundary. *Marine Ecology Progress Series*, **488**, 233-245.

Ragazzola, F., L.C. Foster, A. Form, P.S.L. Anderson, T.H. Hansteen, and J. Fietzke, 2012: Ocean acidification weakens the structural integrity of coralline algae. *Global Change Biology*, **18(9)**, 2804-2812.

Rando, O.J. and K.J. Verstrepen, 2007: Timescales of genetic and epigenetic inheritance. *Cell*, **128(4)**, 655-668.

Ratkowsky, D.A., R.K. Lowry, T.A. McMeekin, A.N. Stokes, and R.E. Chandler, 1983: Model for bacterial culture growth rate throughout the entire biokinetic temperature range. *Journal of Bacteriology*, **154(3)**, 1222-1226.

Rau, G.H., 2011: CO_2 mitigation via capture and chemical conversion in seawater. *Environmental Science & Technology*, **45(3)**, 1088-1092.

Rau, G.H., E.L. McLeod, and O. Hoegh-Guldberg, 2012: The need for new ocean conservation strategies in a high-carbon dioxide world. *Nature Climate Change*, **2(10)**, 720-724.

Raun, A.L. and J. Borum, 2013: Combined impact of water column oxygen and temperature on internal oxygen status and growth of *Zostera marina* seedlings and adult shoots. *Journal of Experimental Marine Biology and Ecology*, **441**, 16-22.

Raven, J.A. and C.M. Scrimgeour, 1997: The influence of anoxia on plants of saline habitats with special reference to the sulphur cycle. *Annals of Botany*, **79**, 79-86.

Raven, J.A., M. Giordano, J. Beardall, and S.C. Maberly, 2012: Algal evolution in relation to atmospheric CO_2: carboxylases, carbon-concentrating mechanisms and carbon oxidation cycles. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **367(1588)**, 493-507.

Reid, P.C., M.F. Borges, and E. Svendsen, 2001: A regime shift in the North Sea circa 1988 linked to changes in the North Sea horse mackerel fishery. *Fisheries Research*, **50(1-2)**, 163-171.

Reipschläger, A. and H.-O. Pörtner, 1996: Metabolic depression during environmental stress: the role of extracellular versus intracellular pH in *Sipunculus nudus*. *Journal of Experimental Biology*, **199(8)**, 1801-1807.

Reipschläger, A., G.E. Nilsson, and H.-O. Pörtner, 1997: A role for adenosine in metabolic depression in the marine invertebrate *Sipunculus nudus*. *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology*, **272(1)**, R350-356.

Reusch, T.B.H. and T.E. Wood, 2007: Molecular ecology of global change. *Molecular Ecology*, **16(19)**, 3973-3992.

Reusch, T.B.H. and P.W. Boyd, 2013: Experimental evolution meets marine phytoplankton. *Evolution*, **67(7)**, 1849-1859.

Reynaud, S., N. Leclercq, S. Romaine-Lioud, C. Ferrier-Pagès, J. Jaubert, and J.-P. Gattuso, 2003: Interacting effects of CO_2 partial pressure and temperature on photosynthesis and calcification in a scleractinian coral. *Global Change Biology*, **9(11)**, 1660-1668.

Richards, E.J., 2006: Inherited epigenetic variation – revisiting soft inheritance. *Nature Reviews Genetics*, **7(5)**, 395-401.

Richards, J.G., A.P. Farrell, and C.J. Brauner (eds.), 2009: *Hypoxia*. Elsevier Academic Press, Amsterdam, 525 pp.

Richardson, A.J. and M.J. Gibbons, 2008: Are jellyfish increasing in response to ocean acidification? *Limnology and Oceanography*, **53(5)**, 2040-2045.

Richardson, A.J. and D.S. Schoeman, 2004: Climate impact on plankton ecosystems in the Northeast Atlantic. *Science*, **305(5690)**, 1609-1612.

Richardson, A.J., A.W. Walne, A.W.G. John, T.D. Jonas, J.A. Lindley, D.W. Sims, D. Stevens, and M. Witt, 2006: Using continuous plankton recorder data. *Progress in Oceanography*, **68(1)**, 27-74.

Richardson, A.J., A. Bakun, G.C. Hays, and M.J. Gibbons, 2009: The jellyfish joyride: causes, consequences and management responses to a more gelatinous future. *Trends in Ecology and Evolution*, **24(6)**, 312-322.

Richier, S., M.E. Kerros, C. de Vargas, L. Haramaty, P.G. Falkowski, and J.-P. Gattuso, 2009: Light-dependent transcriptional regulation of genes of biogeochemical interest in the diploid and haploid life cycle stages of *Emiliania huxleyi*. *Applied and Environmental Microbiology*, **75(10)**, 3366-3369.

Ridgwell, A. and D.N. Schmidt, 2010: Past constraints on the vulnerability of marine calcifiers to massive carbon dioxide release. *Nature Geoscience*, **3(3)**, 196-200.

Riebesell, U., 2004: Effects of CO_2 enrichment on marine phytoplankton. *Journal of Oceanography*, **60(4)**, 719-729.

Riebesell, U., I. Zondervan, B. Rost, P.D. Tortell, R.E. Zeebe, and F.M.M. Morel, 2000: Reduced calcification of marine plankton in response to increased atmospheric CO_2. *Nature*, **407(6802)**, 364-367.

Riebesell, U., K.G. Schulz, R.G.J. Bellerby, M. Botros, P. Fritsche, M. Meyerhöfer, C. Neill, G. Nondal, A. Oschlies, J. Wohlers, and E. Zöllner, 2007: Enhanced biological carbon consumption in a high CO_2 ocean. *Nature*, **450(7169)**, 545-548.

Riebesell, U., R.G.J. Bellerby, H.P. Grossart, and F. Thingstad, 2008: Mesocosm CO_2 perturbation studies: from organism to community level. *Biogeosciences*, **5(4)**, 1157-1164.

Riebesell, U., J.-P. Gattuso, T.F. Thingstad, and J. Middelburg (eds.), 2013: Special Issue: Arctic Ocean Acidification: Pelagic Ecosystem and Biogeochemical Responses during a Mesocosm Study. *Biogeosciences*, www.biogeosciences.net/special_issue120.html.

Ries, J.B., A.L. Cohen, and D.C. McCorkle, 2009: Marine calcifiers exhibit mixed responses to CO_2-induced ocean acidification. *Geology*, **37(12)**, 1131-1134.

Robinson, C., D.K. Steinberg, T.R. Anderson, J. Arístegui, C.A. Carlson, J.R. Frost, J.F. Ghiglione, S. Hernández-Léon, G.A. Jackson, R. Koppelmann, B. Queguiner, O. Ragueneau, F. Rassoulzadegan, B.H. Robison, C. Tamburini, T. Tanaka, K.F. Wishner, and J. Zhang, 2010: Mesopelagic zone ecology and biogeochemistry – a synthesis. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **57(16)**, 1504-1518.

Robinson, R.A., J.A. Learmonth, A.M. Hutson, C.D. MacLeod, T.H. Sparks, D.I. Leech, G.J. Pierce, M.M. Rehfisch, and H.Q.P. Crick, 2005: *Climate Change and Migratory Species*. British Trust for Ornithology (BTO) Research Report 414 for DEFRA, BTO, Thetford, UK, 304 pp.

Rode, K.D., E. Peacock, M. Taylor, I. Stirling, E.W. Born, K.L. Laidre, and Ø. Wiig, 2012: A tale of two polar bear populations: ice habitat, harvest, and body condition. *Population Ecology*, **54(1)**, 3-18.

Rodolfo-Metalpa, R., F. Houlbrèque, É. Tambutté, F. Boisson, C. Baggini, F.P. Patti, R. Jeffree, M. Fine, A. Foggo, J.-P. Gattuso, and J.M. Hall-Spencer, 2011: Coral and mollusc resistance to ocean acidification adversely affected by warming. *Nature Climate Change*, **1(6)**, 308-312.

Rokitta, S.D. and B. Rost, 2012: Effects of CO_2 and their modulation by light in the life-cycle stages of the coccolithophore *Emiliania huxleyi*. *Limnology and Oceanography*, **57(2)**, 607-618.

Romanuk, T.N., Y. Zhou, U. Brose, E.L. Berlow, R.J. Williams, and N.D. Martinez, 2009: Predicting invasion success in complex ecological networks. *Philosophical Transactions of the Royal Society B*, **364**, 1743-1754.

Rose, G. and R.L. O'Driscoll, 2002: Capelin are good for cod: can the northern stock rebuild without them? *ICES Journal of Marine Science*, **59(5)**, 1018-1026.

Rose, J.M., Y. Feng, C.J. Gobler, R. Gutierrez, C.E. Hare, K. Leblanc, and D.A. Hutchins, 2009: Effects of increased pCO_2 and temperature on the North Atlantic spring bloom. II. Microzooplankton abundance and grazing. *Marine Ecology Progress Series*, **388**, 27-40.

Rose, K.A., J.I. Allen, Y. Artioli, M. Barange, J. Blackford, F. Carlotti, R. Cropp, U. Daewel, K. Edwards, K. Flynn, S.L. Hill, R. HilleRisLambers, G. Huse, S. Mackinson, B. Megrey, A. Moll, R. Rivkin, B. Salihoglu, C. Schrum, L. Shannon, Y.-J. Shin, S.L. Smith, C. Smith, C. Solidoro, M. St. John, and M. Zhou, 2010: End-to-end models for the analysis of marine ecosystems: challenges, issues, and next steps. *Marine and Coastal Fisheries*, **2(1)**, 115-130.

Rosegrant, M.W. and S.A. Cline, 2003: Global food security: challenges and policies. *Science*, **302(5652)**, 1917-1919.

Rossoll, D., R. Bermúdez, H. Hauss, K.G. Schulz, U. Riebesell, U. Sommer, and M. Winder, 2012: Ocean acidification-induced food quality deterioration constrains trophic transfer. *PLoS ONE*, **7(4)**, e34737, doi:10.1371/journal.pone.0034737.

Rost, B., U. Riebesell, S. Burkhardt, and D. Sültemeyer, 2003: Carbon acquisition of bloom-forming marine phytoplankton. *Limnology and Oceanography*, **48(1)**, 55-67.

Rost, B., I. Zondervan, and D. Wolf-Gladrow, 2008: Sensitivity of phytoplankton to future changes in ocean carbonate chemistry: current knowledge, contradictions and research directions. *Marine Ecology Progress Series*, **373**, 227-237.

Russell, B.D., C.A. Passarelli, and S.D. Connell, 2011: Forecasted CO_2 modifies the influence of light in shaping subtidal habitat. *Journal of Phycology*, **47(4)**, 744-752.

Russell, L.M., P.J. Rasch, G.M. Mace, R.B. Jackson, J. Shepherd, P. Liss, M. Leinen, D. Schimel, N.E. Vaughan, A.C. Janetos, P.W. Boyd, R.J. Norby, K. Caldeira, J. Merikanto, P. Artaxo, J. Melillo, and M.G. Morgan, 2012: Ecosystem impacts of geoengineering: a review for developing a science plan. *Ambio*, **41(4)**, 350-369.

Rykaczewski, R.R. and J.P. Dunne, 2011: A measured look at ocean chlorophyll trends. *Nature*, **472(7342)**, E5-E6.

Saba, G.K., O. Schofield, J.J. Torres, E.H. Ombres, and D.K. Steinberg, 2012: Increased feeding and nutrient excretion of adult Antarctic krill, *Euphausia superba*, exposed to enhanced carbon dioxide (CO_2). *PLoS ONE*, **7(12)**, e52224, doi:10.1371/journal.pone.0052224.

Saba, V.S., M.A.M. Friedrichs, D. Antoine, R.A. Armstrong, I. Asanuma, M.J. Behrenfeld, A.M. Ciotti, M. Dowell, N. Hoepffner, K.J.W. Hyde, J. Ishizaka, T. Kameda, J. Marra, F. Mélin, A. Morel, J. O'Reilly, M. Scardi, W.O. Smith Jr., T.J. Smyth, S. Tang, J. Uitz, K. Waters, and T.K. Westberry, 2011: An evaluation of ocean color model estimates of marine primary productivity in coastal and pelagic regions across the globe. *Biogeosciences*, **8(2)**, 489-503.

Saba, V.S., C.A. Stock, J.R. Spotila, F.V. Paladino, and P.S. Tomillo, 2012: Projected response of an endangered marine turtle population to climate change. *Nature Climate Change*, **2(11)**, 814-820.

Sabatés, A., P. Martín, J. Lloret, and V. Raya, 2006: Sea warming and fish distribution: the case of the small pelagic fish, *Sardinella aurita*, in the western Mediterranean. *Global Change Biology*, **12(11)**, 2209-2219.

Saito, M.A., J.W. Moffett, S.W. Chisholm, and J.B. Waterbury, 2002: Cobalt limitation and uptake in *Prochlorococcus*. *Limnology and Oceanography*, **47(6)**, 1629-1636.

Saito, M.A., T.J. Goepfert, and J.T. Ritt, 2008: Some thoughts on the concept of colimitation: three definitions and the importance of bioavailability. *Limnology and Oceanography*, **53(1)**, 276-290.

Sala, E. and N. Knowlton, 2006: Global marine biodiversity trends. *Annual Review of Environment and Resources*, **31(1)**, 93-122.

Sallée, J.B., E. Shuckburgh, N. Bruneau, A.J.S. Meijers, T.J. Bracegirdle, and Z. Wang, 2013: Assessment of Southern Ocean mixed-layer depths in CMIP5 models: historical bias and forcing response. *Journal of Geophysical Research: Oceans*, **118(4)**, 1845-1862.

Salvadeo, C., D. Lluch-Belda, A. Gómez-Gallardo, J. Urbán-Ramírez, and C.D. MacLeod, 2010: Climate change and a poleward shift in the distribution of the Pacific white-sided dolphin in the northeastern Pacific. *Endangered Species Research*, **11(1)**, 13-19.

Salvadeo, C., D. Lluch-Belda, S. Lluch-Cota, and M. Mercuri, 2011: Review of long term macro-fauna movement by multi-decadal warming trends in the Northeastern Pacific. In: *Climate Change: Geophysical Foundations and Ecological Effects* [Blanco, J. and H. Kheradmand (eds.)]. InTech, Rijeka, Croatia, pp. 217-230.

Salvadeo, C., S. Lluch-Cota, M. Maravilla-Chávez, S. Álvarez-Castañeda, M. Mercuri, and A. Ortega-Rubio, 2013: Impact of climate change on sustainable management of gray whale (*Eschrichtius robustus*) populations: whale-watching and conservation. *Archives of Biological Sciences*, **65(3)**, 997-1005.

Santidrián Tomillo, P., V.S. Saba, G.S. Blanco, C.A. Stock, F.V. Paladino, and J.R. Spotila, 2012: Climate driven egg and hatchling mortality threatens survival of eastern Pacific leatherback turtles. *PLoS ONE*, **7(5)**, e37602, doi:10.1371/journal.pone.0037602.

Sarker, M.Y., I. Bartsch, M. Olischläger, L. Gutow, and C. Wiencke, 2013: Combined effects of CO_2, temperature, irradiance and time on the physiological performance of *Chondrus crispus* (Rhodophyta). *Botanica Marina*, **56(1)**, 63-74.

Sarmento, H., J.M. Montoya, E. Vázquez-Domínguez, D. Vaqué, and J.M. Gasol, 2010: Warming effects on marine microbial food web processes: how far can we go when it comes to predictions? *Philosophical Transactions of the Royal Society B*, **365(1549)**, 2137-2149.

Sarmiento, J.L. and N. Gruber, 2006: *Ocean Biogeochemical Dynamics*. Princetion University Press, Princeton, NJ, USA, 526 pp.

Sarmiento, J.L., T.M.C. Hughes, R.J. Stouffer, and S. Manabe, 1998: Simulated response of the ocean carbon cycle to anthropogenic climate warming. *Nature*, **393(6682)**, 245-249.

Sarmiento, J.L., R.D. Slater, J. Dunne, A. Gnanadesikan, and M.R. Hiscock, 2010: Efficiency of small scale carbon mitigation by patch iron fertilization. *Biogeosciences*, **7(11)**, 3593-3624.

Scheibner, C. and R.P. Speijer, 2008: Late Paleocene-early Eocene Tethyan carbonate platform evolution – a response to long- and short-term paleoclimatic change. *Earth-Science Reviews*, **90(3-4)**, 71-102.

Schlüter, M.H., A. Merico, K.H. Wiltshire, W. Greve, and H. von Storch, 2008: A statistical analysis of climate variability and ecosystem response in the German Bight. *Ocean Dynamics*, **58(3-4)**, 169-186.

Schlüter, M.H., A. Merico, M. Reginatto, M. Boersma, K.H. Wiltshire, and W. Greve, 2010: Phenological shifts of three interacting zooplankton groups in relation to climate change. *Global Change Biology*, **16(11)**, 3144-3153.

Schöne, B.R., W. Oschmann, J. Rössler, A.D.F. Castro, S.D. Houk, I. Kröncke, W. Dreyer, R. Janssen, H. Rumohr, and E. Dunca, 2003: North Atlantic Oscillation dynamics recorded in shells of a long-lived bivalve mollusk. *Geology*, **31(12)**, 1037-1040.

Sciandra, A., J. Harlay, D. Lefèvre, R. Lemée, P. Rimmelin, M. Denis, and J.-P. Gattuso, 2003: Response of coccolithophorid *Emiliania huxleyi* to elevated partial pressure of CO_2 under nitrogen limitation. *Marine Ecology Progress Series*, **261**, 111-122.

Seibel, B.A., 2011: Critical oxygen levels and metabolic suppression in oceanic oxygen minimum zones. *Journal of Experimental Biology*, **214(2)**, 326-336.

Seki, O., G.L. Foster, D.N. Schmidt, A. Mackensen, K. Kawamura, and R.D. Pancost, 2010: Alkenone and boron-based Pliocene pCO_2 records. *Earth and Planetary Science Letters*, **292(1-2)**, 201-211.

Sen Gupta, A. and B. McNeil, 2012: Variability and change in the ocean. In: *The Future of the World's Climate* [Henderson-Sellers, A. and K. McGuffie (eds.)]. Elsevier, Amsterdam, Netherlands, pp. 141-165.

Shepherd, J., K. Caldeira, P. Cox, J. Haigh, D. Keith, B. Launder, G. Mace, G. MacKerron, J. Pyle, S. Rayner, C. Redgwell, A. Watson, R. Garthwaite, R. Heap, A. Parker, and J. Wilsdon, 2009: *Geoengineering the Climate*. The Royal Society, London, UK, 98 pp.

Sheppard-Brennand, H., N. Soars, S.A. Dworjanyn, A.R. Davis, and M. Byrne, 2010: Impact of ocean warming and ocean acidification on larval development and calcification in the sea urchin *Tripneustes gratilla*. *PLoS ONE*, **5(6)**, e11372, doi:10.1371/journal.pone.0011372.

Sherman, K. and G. Hempel, 2009: *The UNEP Large Marine Ecosystem Report: A Perspective on Changing Conditions in Lmes of the World's Regional Seas*. UNEP Regional Seas Reports and Studies No. 182, United Nations Environment Programme (UNEP), Nairobi, Kenya, 872 pp.

Sherman, K., M. Sissenwine, V. Christensen, A. Duda, G. Hempel, C. Ibe, S. Levin, D. Lluch-Belda, G. Matishov, J. McGlade, M. O'Toole, S. Seitzinger, R. Serra, H.-R. Skjoldal, Q. Tang, J. Thulin, V. Vandeweerd, and K. Zwanenburg, 2005: A global movement toward an ecosystem approach to management of marine resources. *Marine Ecology Progress Series*, **300**, 275-279.

Short, F.T. and H.A. Neckles, 1999: The effects of global climate change on seagrasses. *Aquatic Botany*, **63(3-4)**, 169-196.

Signorini, S.R. and C.R. McClain, 2012: Subtropical gyre variability as seen from satellites. *Remote Sensing Letters*, **3(6)**, 471-479.

Signorini, S.R., R.G. Murtugudde, C.R. McClain, J.R. Christian, J. Picaut, and A.J. Busalacchi, 1999: Biological and physical signatures in the tropical and subtropical Atlantic. *Journal of Geophysical Research*, **104(8)**, 18376-18382.

Simmonds, M.P. and S.J. Isaac, 2007: The impacts of climate change on marine mammals: early signs of significant problems. *Oryx*, **41(1)**, 19-26.

Simpson, S.D., S. Jennings, M.P. Johnson, J.L. Blanchard, P.-J. Schön, D.W. Sims, and M.J. Genner, 2011: Continental shelf-wide response of a fish assemblage to rapid warming of the sea. *Current Biology*, **21(18)**, 1565-1570.

Sissener, E.H. and T. Bjørndal, 2005: Climate change and the migratory pattern for Norwegian spring-spawning herring – implications for management. *Marine Policy*, **29(4)**, 299-309.

Sluijs, A. and H. Brinkhuis, 2009: A dynamic climate and ecosystem state during the Paleocene-Eocene Thermal Maximum: inferences from dinoflagellate cyst assemblages on the New Jersey Shelf. *Biogeosciences*, **6(8)**, 1755-1781.

Smetacek, V. and S. Nicol, 2005: Polar ocean ecosystems in a changing world. *Nature*, **437(7057)**, 362-368.

Smith, K.L., Jr., H.A. Ruhl, B.J. Bett, D.S. Billett, R.S. Lampitt, and R.S. Kaufmann, 2009: Climate, carbon cycling, and deep-ocean ecosystems. *Proceedings of the National Academy of Sciences of the United States of America*, **106(46)**, 19211-19218.

Smith, S.V., 1981: Marine macrophytes as a global carbon sink. *Science*, **211(4484)**, 838-840.

Snyder, M.A., L.C. Sloan, N.S. Diffenbaugh, and J.L. Bell, 2003: Future climate change and upwelling in the California Current. *Geophysical Research Letters*, **30(15)**, 1823, doi:10.1029/2003GL017647.

Sohm, J.A., E.A. Webb, and D.G. Capone, 2011: Emerging patterns of marine nitrogen fixation. *Nature Reviews Microbiology*, **9(7)**, 499-508.

Sorokin, C. and R.W. Krauss, 1962: Effects of temperature & illuminance on *Chlorella* growth uncoupled from cell division. *Plant Physiology*, **37(1)**, 37-42.

Soto, C.G., 2001: The potential impacts of global climate change on marine protected areas. *Reviews in Fish Biology and Fisheries*, **11(3)**, 181-195.

Springer, A.M., J.F. Piatt, V.P. Shuntov, G.B. Van Vliet, V.L. Vladimirov, A.E. Kuzin, and A.S. Perlov, 1999: Marine birds and mammals of the Pacific Subarctic Gyres. *Progress in Oceanography*, **43(2-4)**, 443-487.

Stassen, P., E. Thomas, and R.P. Speijer, 2012: The progression of environmental changes during the onset of the Paleocene-Eocene Thermal Maximum (New Jersey Coastal Plain). *Austrian Journal of Earth Sciences*, **105(1)**, 169-178.

Steinacher, M., F. Joos, T.L. Frölicher, G.-K. Plattner, and S.C. Doney, 2009: Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model. *Biogeosciences*, **6(4)**, 515-533.

Steinacher, M., F. Joos, T.L. Frölicher, L. Bopp, P. Cadule, V. Cocco, S.C. Doney, M. Gehlen, K. Lindsay, J.K. Moore, B. Schneider, and J. Segschneider, 2010: Projected 21st century decrease in marine productivity: a multi-model analysis. *Biogeosciences*, **7(3)**, 979-1005.

Stenevik, E.K. and S. Sundby, 2007: Impacts of climate change on commercial fish stocks in Norwegian waters. *Marine Policy*, **31(1)**, 19-31.

Stige, L.C., G. Ottersen, P. Dalpadado, K.-S. Chan, D. Hjermann, D.L. Lajus, N.A. Yaragina, and N.C. Stenseth, 2010: Direct and indirect climate forcing in a multi-species marine system. *Proceedings of the Royal Society B*, **277(1699)**, 3411-3420.

Stock, C. and J. Dunne, 2010: Controls on the ratio of mesozooplankton production to primary production in marine ecosystems. *Deep-Sea Research Part I: Oceanographic Research Papers*, **57(1)**, 95-112.

Stock, C.A., M.A. Alexander, N.A. Bond, K.M. Brander, W.W.L. Cheung, E.N. Curchitser, T.L. Delworth, J.P. Dunne, S.M. Griffies, M.A. Haltuch, J.A. Hare, A.B. Hollowed, P. Lehodey, S.A. Levin, J.S. Link, K.A. Rose, R.R. Rykaczewski, J.L. Sarmiento, R.J. Stouffer, F.B. Schwing, G.A. Vecchi, and F.E. Werner, 2011: On the use of IPCC-class models to assess the impact of climate on living marine resources. *Progress in Oceanography*, **88(1-4)**, 1-27.

Stolper, D.A., N.P. Revsbech, and D.E. Canfield, 2010: Aerobic growth at nanomolar oxygen concentrations. *Proceedings of the National Academy of Sciences of the United States of America*, **107(44)**, 18755-18760.

Stramma, L., G.C. Johnson, J. Sprintall, and V. Mohrholz, 2008: Expanding oxygen-minimum zones in the tropical oceans. *Science*, **320(5876)**, 655-658.

Stramma, L., S. Schmidtko, L.A. Levin, and G.C. Johnson, 2010: Ocean oxygen minima expansions and their biological impacts. *Deep-Sea Research Part I: Oceanographic Research Papers*, **57(4)**, 587-595.

Stramma, L., E.D. Prince, S. Schmidtko, J. Luo, J.P. Hoolihan, M. Visbeck, D.W.R. Wallace, P. Brandt, and A. Kortzinger, 2012: Expansion of oxygen minimum zones may reduce available habitat for tropical pelagic fishes. *Nature Climate Change*, **2(1)**, 33-37.

Strand, S.E. and G. Benford, 2009: Ocean sequestration of crop residue carbon: recycling fossil fuel carbon back to deep sediments. *Environmental Science & Technology*, **43(4)**, 1000-1007.

Strong, A.E., G. Liu, W. Skirving, and C.M. Eakin, 2011: NOAA's Coral Reef Watch program from satellite observations. *Annals of GIS*, **17(2)**, 83-92.

Stumpp, M., K. Trubenbach, D. Brennecke, M.Y. Hu, and F. Melzner, 2012: Resource allocation and extracellular acid-base status in the sea urchin *Strongylocentrotus droebachiensis* in response to CO_2 induced seawater acidification. *Aquatic Toxicology*, **110-111**, 194-207.

Sumaila, U.R. and W.W.L. Cheung, 2010: *Development and Climate Change: Cost of Adapting Fisheries to Climate Change*. Discussion Paper Number 5, International Bank for Reconstruction and Development/ World Bank, Washington, DC, USA, 37 pp.

Sumaila, U.R., W.W.L. Cheung, V.W.Y. Lam, D. Pauly, and S. Herrick, 2011: Climate change impacts on the biophysics and economics of world fisheries. *Nature Climate Change*, **1(9)**, 449-456.

Sun, J., D.A. Hutchins, Y. Feng, E.L. Seubert, D.A. Caron, and F.-X. Fu, 2011: Effects of changing pCO_2 and phosphate availability on domoic acid production and physiology of the marine harmful bloom diatom *Pseudo-nitzschia* multiseries. *Limnology and Oceanography*, **56(3)**, 829-840.

Sunday, J.M., R.N. Crim, C.D.G. Harley, and M.W. Hart, 2011: Quantifying rates of evolutionary adaptation in response to ocean acidification. *PLoS ONE*, **6(8)**, e22881, doi:10.1371/journal.pone.0022881.

Sunday, J.M., A.E. Bates, and N.K. Dulvy, 2012: Thermal tolerance and the global redistribution of animals. *Nature Climate Change*, **2(9)**, 686-690.

Sverdrup, H.U., 1953: On conditions for the vernal blooming of phytoplankton. *ICES Journal of Marine Science*, **18(3)**, 287-295.

Sydeman, W.J. and S.J. Bograd, 2009: Marine ecosystems, climate and phenology: introduction. *Marine Ecology Progress Series*, **393**, 185-188.

Takai, K., A. Inoue, and K. Horikoshi, 1999: *Thermaerobacter marianensis* gen. nov., sp. nov., an aerobic extremely thermophilic marine bacterium from the 11000 m deep Mariana Trench. *International Journal of Systematic Bacteriology*, **49(2)**, 619-628.

Takai, K., K. Nakamura, T. Toki, U. Tsunogai, M. Miyazaki, J. Miyazaki, H. Hirayama, S. Nakagawa, T. Nunoura, and K. Horikoshi, 2008: Cell proliferation at 122°C and isotopically heavy CH_4 production by a hyperthermophilic methanogen under high-pressure cultivation. *Proceedings of the National Academy of Sciences of the United States of America*, **105(31)**, 10949-10954.

Takasuka, A. and I. Aoki, 2006: Environmental determinants of growth rates for larval Japanese anchovy *Engraulis japonicus* in different waters. *Fisheries Oceanography*, **15(2)**, 139-149.

Takasuka, A., Y. Oozeki, and I. Aoki, 2007: Optimal growth temperature hypothesis: why do anchovy flourish and sardine collapse or vice versa under the same ocean regime? *Canadian Journal of Fisheries and Aquatic Sciences*, **64(5)**, 768-776.

Takasuka, A., Y. Oozeki, and H. Kubota, 2008: Multi-species regime shifts reflected in spawning temperature optima of small pelagic fish in the western North Pacific. *Marine Ecology Progress Series*, **360**, 211-217.

Tatters, A.O., F.-X. Fu, and D.A. Hutchins, 2012: High CO_2 and silicate limitation synergistically increase the toxicity of *Pseudo-nitzschia fraudulenta*. *PLoS ONE*, **7(2)**, e32116, doi:10.1371/journal.pone.0032116.

Tatters, A.O., A. Schnetzer, F. Fu, A.Y.A. Lie, D.A. Caron, and D.A. Hutchins, 2013: Short- versus long-term responses to changing CO_2 in a coastal dinoflagellate bloom: implications for interspecific competitive interactions and community structure. *Evolution*, **67(7)**, 1879-1891.

Taucher, J. and A. Oschlies, 2011: Can we predict the direction of marine primary production change under global warming? *Geophysical Research Letters*, **38(2)**, L02603, doi:10.1029/2010GL045934.

Taylor, A.R., A. Chrachri, G. Wheeler, H. Goddard, and C. Brownlee, 2011: A voltage-gated H^+ channel underlying pH homeostasis in calcifying Coccolithophores. *PLoS Biology*, **9(6)**, e1001085, doi:10.1371/journal.pbio.1001085.

Taylor, C.C., 1958: Cod growth and temperature. *ICES Journal of Marine Science*, **23**, 366-370.

Teneva, L., M. Karnauskas, C.A. Logan, L. Bianucci, J.C. Currie, and J.A. Kleypas, 2012: Predicting coral bleaching hotspots: the role of regional variability in thermal stress and potential adaptation rates. *Coral Reefs*, **31(1)**, 1-12.

Tenreiro, S., M.F. Nobre, F.A. Rainey, C. Miguel, and M.S. Da Costa, 1997: *Thermonema rossianum* sp. nov., a new thermophilic and slightly halophilic species from saline hot springs in Naples, Italy. *International Journal of Systematic Bacteriology*, **47(1)**, 122-126.

Thackeray, S.J., T.H. Sparks, M. Frederiksen, S. Burthe, P.J. Bacon, J.R. Bell, M.S. Botham, T.M. Brereton, P.W. Bright, L. Carvalho, T. Clutton-Brock, A. Dawson, M. Edwards, J.M. Elliott, R. Harrington, D. Johns, I.D. Jones, J.T. Jones, D.I. Leech, D.B. Roy, W.A. Scott, M. Smith, R.J. Smithers, I.J. Winfield, and S. Wanless, 2010: Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. *Global Change Biology*, **16(12)**, 3304-3313.

Thomas, E., 2003: Extinction and food at the seafloor: a high-resolution benthic foraminiferal record across the Initial Eocene Thermal Maximum, Southern Ocean Site 690. In: *Causes and Consequences of Globally Warm Climates in the Early Paleogene* [Wing, S.L., P.D. Gingerich, B. Schmitz, and E. Thomas (eds.)]. Geological Society of America Special Paper 369, Geological Society of America, Boulder, CO, USA, pp. 319-332.

Thomas, E., 2007: Cenozoic mass extinctions in the deep sea: what perturbs the largest habitat on earth? In: *Large Scale Ecosystem Perturbation: Causes and Consequences* [Monechi, S., R. Coccioni, and M.R. Rampino (eds.)]. Geological Society of America Special Paper 424, Geological Society of America, Boulder, CO, USA, pp. 1-23.

Thomas, M.K., C.T. Kremer, C.A. Klausmeier, and E. Litchman, 2012: A global pattern of thermal adaptation in marine phytoplankton. *Science*, **338(6110)**, 1085-1088.

Thomsen, J. and F. Melzner, 2010: Moderate seawater acidification does not elicit long-term metabolic depression in the blue mussel *Mytilus edulis*. *Marine Biology*, **157(12)**, 2667-2676.

Thresher, R.E., B. Tilbrook, S. Fallon, N.C. Wilson, and J. Adkins, 2011: Effects of chronic low carbonate saturation levels on the distribution, growth and skeletal chemistry of deep-sea corals and other seamount megabenthos. *Marine Ecology Progress Series*, **442**, 87-99.

Tittensor, D.P., C. Mora, W. Jetz, H.K. Lotze, D. Ricard, E.V. Berghe, and B. Worm, 2010: Global patterns and predictors of marine biodiversity across taxa. *Nature*, **466(7310)**, 1098-1101.

Tortell, P.D., C.D. Payne, Y. Li, S. Trimborn, B. Rost, W.O. Smith, C. Riesselman, R.B. Dunbar, P. Sedwick, and G.R. DiTullio, 2008: CO_2 sensitivity of Southern Ocean phytoplankton. *Geophysical Research Letters*, **35(4)**, L04605, doi:10.1029/2007GL032583.

Trick, C.G., B.D. Bill, W.P. Cochlan, M.L. Wells, V.L. Trainer, and L.D. Pickell, 2010: Iron enrichment stimulates toxic diatom production in high-nitrate, low-chlorophyll areas. *Proceedings of the National Academy of Sciences of the United States of America*, **107(13)**, 5887-5892.

Trimborn, S., N. Lundholm, S. Thoms, K.U. Richter, B. Krock, P.J. Hansen, and B. Rost, 2008: Inorganic carbon acquisition in potentially toxic and non-toxic diatoms: the effect of pH-induced changes in seawater carbonate chemistry. *Physiologia Plantarum*, **133(1)**, 92-105.

Trotter, J., P. Montagna, M. McCulloch, S. Silenzi, S. Reynaud, G. Mortimer, S. Martin, C. Ferrier-Pagès, J.-P. Gattuso, and R. Rodolfo-Metalpa, 2011: Quantifying the pH 'vital effect' in the temperate zooxanthellate coral *Cladocora caespitosa*: validation of the boron seawater pH proxy. *Earth and Planetary Science Letters*, **303(3-4)**, 163-173.

Tseng, Y.-C., M.Y. Hu, M. Stumpp, L.-Y. Lin, F. Melzner, and P.-P. Hwang, 2013: CO_2-driven seawater acidification differentially affects development and molecular plasticity along life history of fish (*Oryzias latipes*). *Comparative Biochemistry and Physiology A: Molecular and Integrative Physiology*, **165(2)**, 119-130.

Ulloa, O., D.E. Canfield, E.F. DeLong, R.M. Letelier, and F.J. Stewart, 2012: Microbial oceanography of anoxic oxygen minimum zones. *Proceedings of the National Academy of Sciences of the United States of America*, **109(40)**, 15996-16003.

UNWTO, 2008: *Climate Change and Tourism – Responding to Global Challenges*. World Tourism Organization and the United Nations Environment Programme, Madrid, Spain, 272 pp.

Urban, M.C., J.J. Tewksbury, and K.S. Sheldon, 2012: On a collision course: competition and dispersal differences create no-analogue communities and cause extinctions during climate change. *Proceedings of the Royal Society B*, **279**, 2072-2080.

Utne-Palm, A.C., A.G. Salvanes, B. Currie, S. Kaartvedt, G.E. Nilsson, V.A. Braithwaite, J.A. Stecyk, M. Hundt, M. van der Bank, B. Flynn, G.K. Sandvik, T.A. Klevjer, A.K. Sweetman, V. Bruchert, K. Pittman, K.R. Peard, I.G. Lunde, R.A. Strandabo, and M.J. Gibbons, 2010: Trophic structure and community stability in an overfished ecosystem. *Science*, **329(5989)**, 333-336.

Valdimarsson, H., O.S. Astthorsson, and J. Palsson, 2012: Hydrographic variability in Icelandic waters during recent decades and related changes in distribution of some fish species. *ICES Journal of Marine Science*, **69(5)**, 816-825.

Van Houtan, K.S. and O.L. Bass, 2007: Stormy oceans are associated with declines in sea turtle hatching. *Current Biology*, **17(15)**, 590-591.

Van Houtan, K.S. and J.M. Halley, 2011: Long-term climate forcing in loggerhead sea turtle nesting. *PLoS ONE*, **6(4)**, e19043, doi:10.1371/journal.pone.0019043.

Vaquer-Sunyer, R. and C.M. Duarte, 2008: Thresholds of hypoxia for marine biodiversity. *Proceedings of the National Academy of Sciences of the United States of America*, **105(40)**, 15452-15457.

Vaquer-Sunyer, R. and C.M. Duarte, 2011: Temperature effects on oxygen thresholds for hypoxia in marine benthic organisms. *Global Change Biology*, **17(5)**, 1788-1797.

Vargas, F.H., R.C. Lacy, P.J. Johnson, A. Steinfurth, R.J.M. Crawford, P. Dee Boersma, and D.W. Macdonald, 2007: Modelling the effect of El Niño on the persistence of small populations: the Galápagos penguin as a case study. *Biological Conservation*, **137(1)**, 138-148.

Vásquez-Bedoya, L.F., A.L. Cohen, D.W. Oppo, and P. Blanchon, 2012: Corals record persistent multidecadal SST variability in the Atlantic Warm Pool since 1775 AD. *Paleoceanography*, **27**, PA3231, doi:10.1029/2012PA002313.

Vaughan, N.E. and T.M. Lenton, 2011: A review of climate geoengineering proposals. *Climatic Change*, **109(3-4)**, 745-790.

Vecchi, G.A. and B.J. Soden, 2007: Increased tropical Atlantic wind shear in model projections of global warming. *Geophysical Research Letters*, **34**, L08702, doi:10.1029/2006GL028905.

Vélez-Belchí, P., A. Hernández-Guerra, E. Fraile-Nuez, and V. Benítez-Barrios, 2010: Changes in temperature and salinity tendencies of the upper subtropical North Atlantic ocean at 24.5°N. *Journal of Physical Oceanography*, **40(11)**, 2546-2555.

Venn, A.A., E. Tambutté, M. Holcomb, J. Laurent, D. Allemand, and S. Tambutté, 2013: Impact of seawater acidification on pH at the tissue-skeleton interface and alcification in reef corals. *Proceedings of the National Academy of Sciences of the United States of America*, **110(5)**, 1634-1639.

Ventura, S., C. Viti, R. Pastorelli, and L. Giovannetti, 2000: Revision of species delineation in the genus *Ectothiorhodospira*. *International Journal of Systematic and Evolutionary Microbiology*, **50(2)**, 583-591.

Vermeij, G.J. and E.J. Petuch, 1986: Differential extinction in tropical American molluscs: endemism, architecture, and the Panama land bridge. *Malacologia*, **27(1)**, 29-41.

Veron, J.E.N., O. Hoegh-Guldberg, T.M. Lenton, J.M. Lough, D.O. Obura, P. Pearce-Kelly, C.R. Sheppard, M. Spalding, M.G. Stafford-Smith, and A.D. Rogers, 2009: The coral reef crisis: the critical importance of < 350 ppm CO_2. *Marine Pollution Bulletin*, **58(10)**, 1428-1436.

Veron, J.E.N., 2011: Ocean acidification and coral reefs: an emerging big picture. *Diversity*, **3(2)**, 262-274.

Vetter, R.D., E.A. Lynn, M. Garza, and A.S. Costa, 1994: Depth zonation and metabolic adaptation in Dover sole, *Microstomus pacificus*, and other deep-living flatfishes: factors that affect the sole. *Marine Biology*, **120(1)**, 145-159.

Vezzoli, A., M. Gussoni, F. Greco, L. Zetta, and P. Cerretelli, 2004: Temperature and pH dependence of energy balance by ^{31}P- and ^{1}H-MRS in anaerobic frog muscle. *Biochimica et Biophysica Acta*, **1608(2-3)**, 163-170.

Vezzulli, L., C. Pruzzo, A. Huq, and R.R. Colwell, 2010: Environmental reservoirs of *Vibrio cholerae* and their role in cholera. *Environmental Microbiology Reports*, **2(1)**, 27-33.

Vitasse, Y., C.C. Bresson, A. Kremer, R. Michalet, and S. Delzon, 2010: Quantifying phenological plasticity to temperature in two temperate tree species. *Functional Ecology*, **24(6)**, 1211-1218.

Vogt, M., M. Steinke, S. Turner, A. Paulino, M. Meyerhofer, U. Riebesell, C. LeQuéré, and P. Liss, 2008: Dynamics of dimethylsulphoniopropionate and dimethylsulphide under different CO_2 concentrations during a mesocosm experiment. *Biogeosciences*, **5**, 407-419.

Votier, S.C., B.J. Hatchwell, A. Beckerman, R.H. McCleery, F.M. Hunter, J. Pellatt, M. Trinder, and T.R. Birkhead, 2005: Oil pollution and climate have wide-scale impacts on seabird demographics. *Ecology Letters*, **8(11)**, 1157-1164.

Walther, K., F.J. Sartoris, C. Bock, and H.-O. Pörtner, 2009: Impact of anthropogenic ocean acidification on thermal tolerance of the spider crab *Hyas araneus*. *Biogeosciences*, **6(10)**, 2207-2215.

Walther, K., K. Anger, and H.-O. Pörtner, 2010: Effects of ocean acidification and warming on the larval development of the spider crab *Hyas araneus* from different latitudes (54° vs. 79°N). *Marine Ecology Progress Series*, **417**, 159-170.

Walther, K., F.J. Sartoris, and H.-O. Pörtner, 2011: Impacts of temperature and acidification on larval calcification of the spider crab *Hyas araneus* from different latitudes (54° vs. 79°N). *Marine Biology*, **158(9)**, 2043-2053.

Wara, M.W., A.C. Ravelo, and M.L. Delaney, 2005: Permanent El Niño-like conditions during the Pliocene warm period. *Science*, **309(5735)**, 758-761.

Ware, D.M. and R.E. Thomson, 2005: Bottom-up ecosystem trophic dynamics determine fish production in the northeast Pacific. *Science*, **308(5726)**, 1280-1284.

Watanabe, Y.W., M. Shigemitsu, and K. Tadokoro, 2008: Evidence of a change in oceanic fixed nitrogen with decadal climate change in the North Pacific subpolar region. *Geophysical Research Letters*, **35(1)**, L01602, doi:10.1029/2007GL032188.

Watson, A.J., U. Schuster, D.C.E. Bakker, N.R. Bates, A. Corbière, M. González-Dávila, T. Friedrich, J. Hauck, C. Heinze, T. Johannessen, A. Körtzinger, N. Metzl, J. Olafsson, A. Olsen, A. Oschlies, X.A. Padin, B. Pfeil, J.M. Santana-Casiano, T. Steinhoff, M. Telszewski, A.F. Rios, D.W.R. Wallace, and R. Wanninkhof, 2009: Tracking the variable North Atlantic sink for atmospheric CO_2. *Science*, **326(5958)**, 1391-1393.

Webb, A.E., L.R. Leighton, S.A. Schellenberg, E.A. Landau, and E. Thomas, 2009: Impact of the Paleocene-Eocene thermal maximum on deep-ocean microbenthic community structure: using rank-abundance curves to quantify paleoecological response. *Geology*, **37(9)**, 783-786.

Weinbauer, M.G., X. Mari, and J.-P. Gattuso, 2011: Effects of ocean acidification on the diversity and activity of heterotrophic marine microorganisms. In: *Ocean Acidification* [Gattuso, J.-P. and L. Hansson (eds.)]. Oxford University Press, Oxford, UK, pp. 83-98.

Wernberg, T., D.A. Smale, F. Tuya, M.S. Thomsen, T.J. Langlois, T. de Bettignies, S. Bennett, and C.S. Rousseaux, 2013: An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. *Nature Climate Change*, **3(1)**, 78-82.

Westbrook, G.K., K.E. Thatcher, E.J. Rohling, A.M. Piotrowski, H. Pälike, A.H. Osborne, E.G. Nisbet, T.A. Minshull, M. Lanoisellé, R.H. James, V. Hühnerbach, D. Green, R.E. Fisher, A.J. Crocker, A. Chabert, C. Bolton, A. Beszczynska-Möller, C. Berndt, and A. Aquilina, 2009: Escape of methane gas from the seabed along the West Spitsbergen continental margin. *Geophysical Research Letters*, **36(15)**, L15608, doi:10.1029/2009GL039191.

Wethey, D.S., S.A. Woodin, T.J. Hilbish, S.J. Jones, F.P. Lima, and P.M. Brannock, 2011: Response of intertidal populations to climate: effects of extreme events versus long term change. *Journal of Experimental Marine Biology and Ecology*, **400(1-2)**, 132-144.

Whiteley, N.M., 2011: Physiological and ecological responses of crustaceans to ocean acidification. *Marine Ecology Progress Series*, **430**, 257-271.

Whitney, F.A., 2011: Nutrient variability in the mixed layer of the subarctic Pacific Ocean, 1987-2010. *Journal of Oceanography*, **67(4)**, 481-492.

Williams, J.W. and S.T. Jackson, 2007: Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology and the Environment*, **5(9)**, 475-482.

Williamson, P. and C. Turley, 2012: Ocean acidification in a geoengineering context. *Philosophical Transactions of the Royal Society A*, **370(1974)**, 4317-4342.

Williamson, P., R.T. Watson, G. Mace, P. Artaxo, R. Bodle, V. Galaz, A. Parker, D. Santillo, C. Vivian, D. Cooper, J. Webbe, A. Cung, and E. Woods, 2012: *Impacts of Climate-Related Geoengineering on Biological Diversity. Part I: Geoengineering in Relation to the Convention on Biological Diversity: Technical and Regulatory Matters*. Secretariat of the Convention on Biological Diversity, Montreal, Technical Series No. 66, 152 pp.

Wilson, K.J., J. Falkingham, H. Melling, and R. De Abreu, 2004: Shipping in the Canadian Arctic: other possible climate change scenarios. *Geoscience and Remote Sensing Symposium Proceedings*, **3**, 1853-1856.

Wilson, R., A. Tudhope, P. Brohan, K. Briffa, T. Osborn, and S. Tett, 2006: Two-hundred-fifty years of reconstructed and modeled tropical temperatures. *Journal of Geophysical Research*, **111(C10)**, C10007, doi:10.1029/2005JC003188.

Wilson, S.E., D.K. Steinberg, and K.O. Buesseler, 2008: Changes in fecal pellet characteristics with depth as indicators of zooplankton repackaging of particles in the mesopelagic zone of the subtropical and subarctic North Pacific Ocean. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **55(14-15)**, 1636-1647.

Wiltshire, K., A. Kraberg, I. Bartsch, M. Boersma, H.-D. Franke, J. Freund, C. Gebühr, G. Gerdts, K. Stockmann, and A. Wichels, 2010: Helgoland roads, North Sea: 45 years of change. *Estuaries and Coasts*, **33(2)**, 295-310.

Witt, M.J., L.A. Hawkes, M.H. Godfrey, B.J. Godley, and A.C. Broderick, 2010: Predicting the impacts of climate change on a globally distributed species: the case of the loggerhead turtle. *Journal of Experimental Biology*, **213**, 901-911.

Wittmann, A.C. and H.-O. Pörtner, 2013: Sensitivities of extant animal taxa to ocean acidification. *Nature Climate Change*, **3**, 995-1001.

Woese, C.R., O. Kandler, and M.L. Wheelis, 1990: Towards a natural system of organisms: proposal for the domains Archaea, Bacteria, and Eucarya. *Proceedings of the National Academy of Sciences of the United States of America*, **87(12)**, 4576-4579.

Wohlers-Zöllner, J., P. Breithaupt, K. Walther, K. Jürgens, and U. Riebesell, 2011: Temperature and nutrient stoichiometry interactively modulate organic matter cycling in a pelagic algal-bacterial community. *Limnology and Oceanography*, **56(2)**, 599-610.

Wolf, S.G., M.A. Snyder, W.J. Sydeman, D.F. Doak, and D.A. Croll, 2010: Predicting population consequences of ocean climate change for an ecosystem sentinel, the seabird Cassin's auklet. *Global Change Biology*, **16(7)**, 1923-1935.

Wolff, G.A., D.S.M. Billett, B.J. Bett, J. Holtvoeth, T. FitzGeorge-Balfour, E.H. Fisher, I. Cross, R. Shannon, I. Salter, B. Boorman, N.J. King, A. Jamieson, and F. Chaillan, 2011: The effects of natural iron fertilisation on deep-sea ecology: the Crozet plateau, Southern Indian Ocean. *PLoS ONE*, **6(6)**, e20697, doi:10.1371/journal.pone.0020697.

Wood, H.L., J.I. Spicer, and S. Widdicombe, 2008: Ocean acidification may increase calcification rates, but at a cost. *Proceedings of the Royal Society B*, **275(1644)**, 1767-1773.

Wood, R., 1999: *Reef Evolution*. Oxford University Press, Oxford, UK, 414 pp.

Woodworth-Jefcoats, P.A., J.J. Polovina, J.P. Dunne, and J.L. Blanchard, 2013: Ecosystem size structure response to 21st century climate projection: large fish abundance decreases in the central North Pacific and increases in the California Current. *Global Change Biology*, **19(3)**, 724-733.

Wootton, J.T., C.A. Pfister, and J.D. Forester, 2008: Dynamic patterns and ecological impacts of declining ocean pH in a high-resolution multi-year dataset. *Proceedings of the National Academy of Sciences of the United States of America*, **105(48)**, 18848-18853.

Worm, B., R. Hilborn, J.K. Baum, T.A. Branch, J.S. Collie, C. Costello, M.J. Fogarty, E.A. Fulton, J.A. Hutchings, S. Jennings, O.P. Jensen, H.K. Lotze, P.M. Mace, T.R. McClanahan, C. Minto, S.R. Palumbi, A.M. Parma, D. Ricard, A.A. Rosenberg, R. Watson, and D. Zeller, 2009: Rebuilding global fisheries. *Science*, **325(5940)**, 578-585.

Zachos, J.C., U. Röhl, S.A. Schellenberg, A. Sluijs, D.A. Hodell, D.C. Kelly, E. Thomas, M. Nicolo, I. Raffi, L.J. Lourens, H. McCarren, and D. Kroon, 2005: Rapid acidification of the ocean during the Paleocene-Eocene Thermal Maximum. *Science*, **308(5728)**, 1611-1615.

Zeebe, R.E. and P. Westbroek, 2003: A simple model for the $CaCO_3$ saturation state of the ocean: the "Strangelove", the "Neritan", and the "Cretan" Ocean. *Geochemistry Geophysics Geosystems*, **4(12)**, 1104, doi:10.1029/2003GC000538.

Zeebe, R.E., J.C. Zachos, and G.R. Dickens, 2009: Carbon dioxide forcing alone insufficient to explain Palaeocene-Eocene Thermal Maximum warming. *Nature Geoscience*, **2(8)**, 576-580.

Zhang, J., D. Gilbert, A.J. Gooday, L. Levin, S.W.A. Naqvi, J.J. Middelburg, M. Scranton, W. Ekau, A. Peña, B. Dewitte, T. Oguz, P.M.S. Monteiro, E. Urban, N.N. Rabalais, V. Ittekkot, W.M. Kemp, O. Ulloa, R. Elmgren, E. Escobar-Briones, and A.K. Van der Plas, 2010: Natural and human-induced hypoxia and consequences for coastal areas: synthesis and future development. *Biogeosciences*, **7(5)**, 1443-1467.

Zondervan, I., R.E. Zeebe, B. Rost, and U. Riebesell, 2001: Decreasing marine biogenic calcification: a negative feedback on rising atmospheric pCO_2. *Global Biogeochemical Cycles*, **15(2)**, 507-516.

Zondervan, I., B. Rost, and U. Riebesell, 2002: Effect of CO_2 concentration on the PIC/POC ratio in the coccolithophore *Emiliania huxleyi* grown under light-limiting conditions and different daylengths. *Journal of Experimental Marine Biology and Ecology*, **272(1)**, 55-70.

7 Food Security and Food Production Systems

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This chapter should be cited as:
Porter, J.R., L. Xie, A.J. Challinor, K. Cochrane, S.M. Howden, M.M. Iqbal, D.B. Lobell, and M.I. Travasso, 2014: Food security and food production systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485-533.

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Executive Summary

The effects of climate change on crop and terrestrial food production are evident in several regions of the world (*high confidence*). Negative impacts of climate trends have been more common than positive ones. {Figures 7-2, 7-7} Positive trends are evident in some high-latitude regions (*high confidence*). Since AR4, there have been several periods of rapid food and cereal price increases following climate extremes in key producing regions, indicating a sensitivity of current markets to climate extremes, among other factors. {Figure 7-3, Table 18-3} Several of these climate extremes were made more likely as the result of anthropogenic emissions (*medium confidence*). {Table 18-3}

Climate trends are affecting the abundance and distribution of harvested aquatic species, both freshwater and marine, and aquaculture production systems in different parts of the world. {7.2.1.2, 7.3.2.4, 7.4.2} These are expected to continue with negative impacts on nutrition and food security for especially vulnerable people, particularly in some tropical developing countries {7.3.3.2}, but with benefits in other regions that become more favorable for aquatic food production (*medium confidence*). {7.5.1.1.2}

Studies have documented a large negative sensitivity of crop yields to extreme daytime temperatures around 30°C. {WGII AR4 Chapter 5, 7.3.2.1} These sensitivities have been identified for several crops and regions and exist throughout the growing season (*high confidence*). Several studies report that temperature trends are important for determining both past and future impacts of climate change on crop yields at sub-continental to global scales (*medium confidence*). {7.3.2, Box 7-1} At scales of individual countries or smaller, precipitation projections remain important but uncertain factors for assessing future impacts (*high confidence*). {7.3.2, Box 7-1}

Evidence since AR4 confirms the stimulatory effects of carbon dioxide (CO_2) in most cases and the damaging effects of elevated tropospheric ozone (O_3) on crop yields (*high confidence*). Experimental and modeling evidence indicates that interactions between CO_2 and O_3, mean temperature and extremes, water, and nitrogen are nonlinear and difficult to predict (*medium confidence*). {7.3.2.1, Figure 7-2}

Changes in climate and CO_2 concentration will enhance the distribution and increase the competitiveness of agronomically important and invasive weeds (*medium confidence*). Rising CO_2 may reduce the effectiveness of some herbicides (*low confidence*). The effects of climate change on disease pressure on food crops are uncertain, with evidence pointing to changed geographical ranges of pests and diseases but less certain changes in disease intensity (*low confidence*). {7.3.2.3}

All aspects of food security are potentially affected by climate change, including food access, utilization, and price stability (*high confidence*). {7.3.3.1, Table 7-1} There remains limited quantitative understanding of how non-production elements of food security will be affected, and of the adaptation possibilities in these domains. Nutritional quality of food and fodder, including protein and micronutrients, is negatively affected by elevated CO_2, but these effects may be counteracted by effects of other aspects of climate change (*medium confidence*). {7.3.2.5}

For the major crops (wheat, rice, and maize) in tropical and temperate regions, climate change without adaptation will negatively impact production for local temperature increases of 2°C or more above late-20th-century levels, although individual locations may benefit (*medium confidence*). {7.4, Figure 7-4} Projected impacts vary across crops and regions and adaptation scenarios, with about 10% of projections for the period 2030–2049 showing yield gains of more than 10% and about 10% of projections showing yield losses of more than 25%, compared to the late 20th century. {Figure 7-5} After 2050, the risk of more severe impacts increases. {Figure 7-5} Regional Chapters 22 (Africa), 23 (Europe), 24 (Asia), 27 (Central and South America), and Box 7-1 show crop production to be consistently and negatively affected by climate change in the future in low-latitude countries, while climate change may have positive or negative effects in northern latitudes (*high confidence*). Climate change will increase progressively the inter-annual variability of crop yields in many regions (*medium confidence*). {Figure 7-6}

On average, agronomic adaptation improves yields by the equivalent of ~15-18% of current yields {Figure 7-8, Table 7-2}, but the effectiveness of adaptation is highly variable (*medium confidence*) ranging from potential dis-benefits to negligible to very substantial (*medium confidence*). {7.5.1.1.1} Projected benefits of adaptation are greater for crops in temperate, rather than tropical, regions (*medium confidence*) {7.5.1.1.1, Figures 7-4, 7-7}, with wheat- and rice-based systems more adaptable than those of maize (*low confidence*). {Figure 7-4} Some adaptation options are more effective than others (*medium confidence*). {Table 7-2}

Global temperature increases of ~4°C or more above late-20th-century levels, combined with increasing food demand, would pose large risks to food security globally and regionally (*high confidence*). Risks to food security are generally greater in low-latitude areas. {Box 7-1, Table 7-3, Figures 7-4, 7-5, 7-7}

Changes in temperature and precipitation, without considering effects of CO_2, will contribute to increased global food prices by 2050, with estimated increases ranging from 3 to 84% (*medium confidence*). Projections that include the effects of CO_2 changes, but ignore O_3 and pest and disease impacts, indicate that global price increases are about *as likely as not*, with a range of projected impacts from –30% to +45% by 2050. {7.4.4}

Adaptation in fisheries, aquaculture, and livestock production will potentially be strengthened by adoption of multi-level adaptive strategies to minimize negative impacts. Key adaptations for fisheries and aquaculture include policy and management to maintain ecosystems in a state that is resilient to change, enabling occupational flexibility, and development of early warning systems for extreme events (*medium confidence*). {7.5.1.1.2} Adaptations for livestock systems center on adjusting management to the available resources, using breeds better adapted to the prevailing climate and removing barriers to adaptation such as improving credit access (*medium confidence*). {7.5.1.1.3}

A range of potential adaptation options exist across all food system activities, not just in food production, but benefits from potential innovations in food processing, packaging, transport, storage, and trade are insufficiently researched. {7.1, 7.5, 7.6, Figures 7-1, 7-7, 7-8} More observational evidence is needed on the effectiveness of adaptations at all levels of the food system. {7.6}

7.1. Introduction and Context

Many definitions of food security exist, and these have been the subject of much debate. As early as 1992, Maxwell and Smith (1992) reviewed more than 180 items discussing concepts and definitions, and more definitions have been formulated since (DEFRA, 2006). Whereas many earlier definitions centered on food production, more recent definitions highlight access to food, in keeping with the 1996 World Food Summit definition (FAO, 1996) that food security is met when "all people, at all times, have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life." Worldwide attention on food access was given impetus by the food "price spike" in 2007–2008, triggered by a complex set of long- and short-term factors (FAO, 2009b; von Braun and Torero, 2009). FAO concluded, "provisional estimates show that, in 2007, 75 million more people were added to the total number of undernourished relative to 2003–05" (FAO, 2008); this is arguably a low-end estimate (Headey and Fan, 2010). More than enough food is currently produced per capita to feed the global population, yet about 870 million people remained hungry in the period from 2010 to 2012 (FAO et al., 2012). The questions for this chapter are how far climate and its change affect current food production systems and food security and the extent to which they will do so in the future (Figure 7-1).

7.1.1. Food Systems

A food system is all processes and infrastructure involved in satisfying a population's food security, that is, the gathering/catching, growing, harvesting (production aspects), storing, processing, packaging, transporting, marketing, and consuming of food, and disposing of food waste (non-production aspects). It includes food security outcomes of these activities related to availability and utilization of, and access to, food as well as other socioeconomic and environmental factors (Ericksen, 2008; Ericksen et al., 2010; Ingram, 2011). This chapter synthesizes and evaluates evidence for the impacts of climate on both production and non-production elements and their adaptation to climate change (Figure 7-1).

The impacts of climate change on food systems are expected to be widespread, complex, geographically and temporally variable, and profoundly influenced by socioeconomic conditions (Vermeulen et al., 2012). Changes in food system drivers give rise to changes in food security outcomes (*medium evidence*, *high agreement*), but often researchers consider only the impacts on the food production element of food security (Figure 7-1). Efforts to increase food production are nevertheless increasingly important as 60% more food will be needed by 2050 given current food consumption trends and assuming no significant reduction in food waste (FAO et al., 2012).

7.1.2. The Current State of Food Security

Most people on the planet currently have enough food to eat. The vast majority of undernourished people live in developing countries (*medium evidence*, *medium agreement*), when estimated based on aggregate national calorie availability and assumptions about food distribution and nutritional requirements. More precise estimates are possible with detailed household surveys, which often show a higher incidence of food insecurity than estimated by FAO. Using food energy deficit as the measure of food insecurity, Smith et al. (2006) estimated average rates of food insecurity of 59% for 12 African countries, compared to a 39% estimate from FAO for the same period (Smith et al., 2006). While there is *medium evidence*, *medium agreement* on absolute numbers, there is *robust evidence*, *high agreement* that sub-Saharan Africa has the highest proportion of food-insecure people, with an estimated regional average of 26.8% of the population undernourished in 2010–2012, and where rates higher than 50% can be found (FAO et al., 2012). The largest numbers of food-insecure persons are found in South Asia, which has roughly 300 million undernourished (FAO et al., 2012). In addition to common measures of calorie availability, food security can be broadened to include nutritional aspects based on the diversity of diet including not only staple foods but also vegetables, fruits, meat, milk, eggs, and fortified foods (FAO, 2011). There is *robust evidence* and *high agreement* that lack of essential micronutrients such as zinc and vitamin A affect hundreds of millions of additional people (Lopez et al., 2006; Pinstrup-Andersen, 2009).

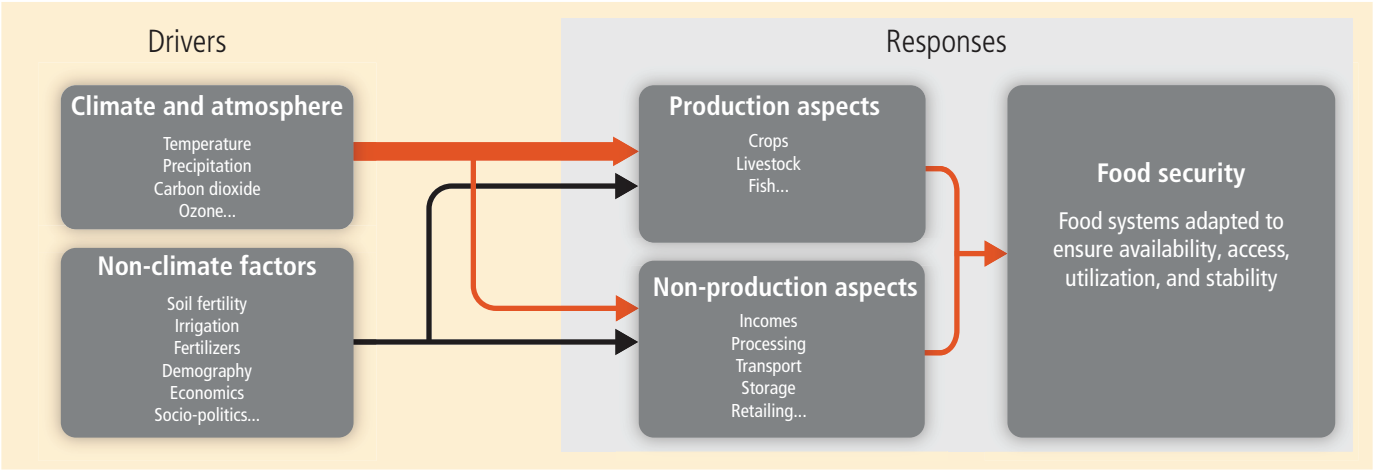

Figure 7-1 | Main issues of the chapter. Drivers are divided into climate and non-climate elements, affecting production and non-production elements of food systems, thereafter combining to provide food security. The thickness of the red lines is indicative of the relative availability of refereed publications on the two elements.

Food insecurity is closely tied to poverty; globally about 25 to 30% of poor people, measured using a US$1 to US$2 per day standard, live in urban areas (Ravallion et al., 2007; IFAD, 2010). Most poor countries have a larger fraction of people living in rural areas and poverty rates tend to be higher in rural settings (by slight margins in South Asia and Africa, and by large margins in China). In Latin America, poverty is more skewed to urban areas, with roughly two-thirds of the poor in urban areas, a proportion that has been growing in the past decade (*medium evidence*, *medium agreement*). Rural areas will continue to have the majority of poor people for at least the next few decades, even as population growth is higher in urban areas (*medium evidence*, *medium agreement*) (Ravallion et al., 2007; IFAD, 2010).

The effects of price volatility are distinct from the effects of gradual price rises, for two main reasons. First, rapid shifts make it difficult for the poor to adjust their activities to favor producing higher value items. Second, increased volatility leads to greater uncertainty about the future and can dampen willingness to invest scarce resources into productivity enhancing assets, such as fertilizer purchases in the case of farmers or rural infrastructure in the case of governments. Several factors have been found to contribute to increased price volatility: poorly articulated local markets, increased incidence of adverse weather events, and greater reliance on production areas with high exposure to such risks, biofuel mandates, and increased links between energy and agricultural markets (World Bank, 2012). Vulnerability to food price volatility depends on the degree to which households and countries are net food purchasers; the level of integration into global, regional, and local markets; and their relative degree of volatility, which in turn is conditional on their respective governance (*robust evidence*, *medium agreement*) (HLPE, 2011; World Bank, 2012).

7.1.3. Summary from AR4

Food systems as integrated drivers, activities, and outcomes for food security did not feature strongly in AR4. Summary points from AR4 were that, with *medium confidence*, in mid- to high-latitude regions moderate warming will raise crop and pasture yields. Sight warming will decrease yields in low-latitude regions. Extreme climate and weather events will, with *high confidence*, reduce food production. The benefits of adaptation vary with crops and across regions and temperature changes; however, on average, they provide approximately a 10% yield benefit when compared with yields when no adaptation is used (WGII AR4 Section 5.5.1). Adaptive capacity is projected to be exceeded in low-latitude areas with temperature increases of more than 3°C. Local extinctions of particular fish species are expected at the edges of their ranges (*high confidence*) and have serious negative impacts on fisheries (*medium confidence*).

7.2. Observed Impacts, with Detection and Attribution

7.2.1. Food Production Systems

Formal detection of impacts requires that observed changes be compared to a clearly specified baseline that characterizes behavior in the absence of climate change (Chapter 18). For food production systems, the number and strength of non-climate drivers, such as cultivar improvement or increased use of irrigation and fertilizers in the case of crops, make defining a clear baseline extremely difficult. Most non-climatic factors are not very well characterized in terms of spatial and temporal distributions, and the relationships between these factors and specific outcomes of interest (e.g., crop or fish production) are often difficult to quantify.

Attribution of any observed changes to climate trends are further complicated by the fact that models linking climate and agriculture must, implicitly or explicitly, make assumptions about farmer behavior. In most cases, models implicitly assume that farming practices or technologies did not adjust in response to climate over the period of interest. This assumption can be defended in some cases based on ancillary data on practices, or based on small differences between using models with and without adaptation (Schlenker and Roberts, 2009). However, in some instances the relationship between climate conditions and crop production has been shown to change over time because of management changes, such as introduction of irrigation or changes in crop varieties (Zhang et al, 2008; Liu et al., 2009; Sakurai et al., 2012).

7.2.1.1. Crop Production

Many studies of cropping systems have estimated impacts of observed climate changes on crop yields over the past half century, although they typically do not attempt to compare observed yields to a counterfactual baseline, and thus are not formal detection and attribution studies. These studies employ both mechanistic and statistical approaches (Section 7.3.1), and estimate impacts by running the models with observed historical climate and then computing trends in modeled outcomes. Based on these studies, there is *medium confidence* that climate trends have negatively affected wheat and maize production for many regions (Figure 7-2) (*medium evidence*, *high agreement*). Because many of these regional studies are for major producers, and a global study (Lobell et al., 2011a) estimated negative impacts on these crops, there is also *medium confidence* for negative impacts on global aggregate production of wheat and maize. Effects on rice and soybean yields have been small in major production regions and globally (Figure 7-2) (*medium evidence*, *high agreement*). There is also *high confidence* that warming has benefitted crop production in some high-latitude regions, such as northeast China or the UK (Jaggard et al., 2007; Chen et al., 2010; Supit et al., 2010; Gregory and Marshall, 2012).

More difficult to quantify with models is the impact of very extreme events on cropping systems, as by definition these occur very rarely and models cannot be adequately calibrated and tested. Table 18-3 lists some notable extremes over the past decade, and the impacts on cropping systems. Despite the difficulty of modeling the impacts of these events, they clearly have sizable impacts (Sanchez et al. 2014) that are apparent immediately or soon after the event, and therefore not easily confused with effects of more slowly moving factors. For a subset of these events, climate research has evaluated whether anthropogenic activity has increased or decreased their likelihood (Table 18-3).

A sizable fraction of crop modeling studies were concerned with production for individual sites or provinces, spatial scales below which

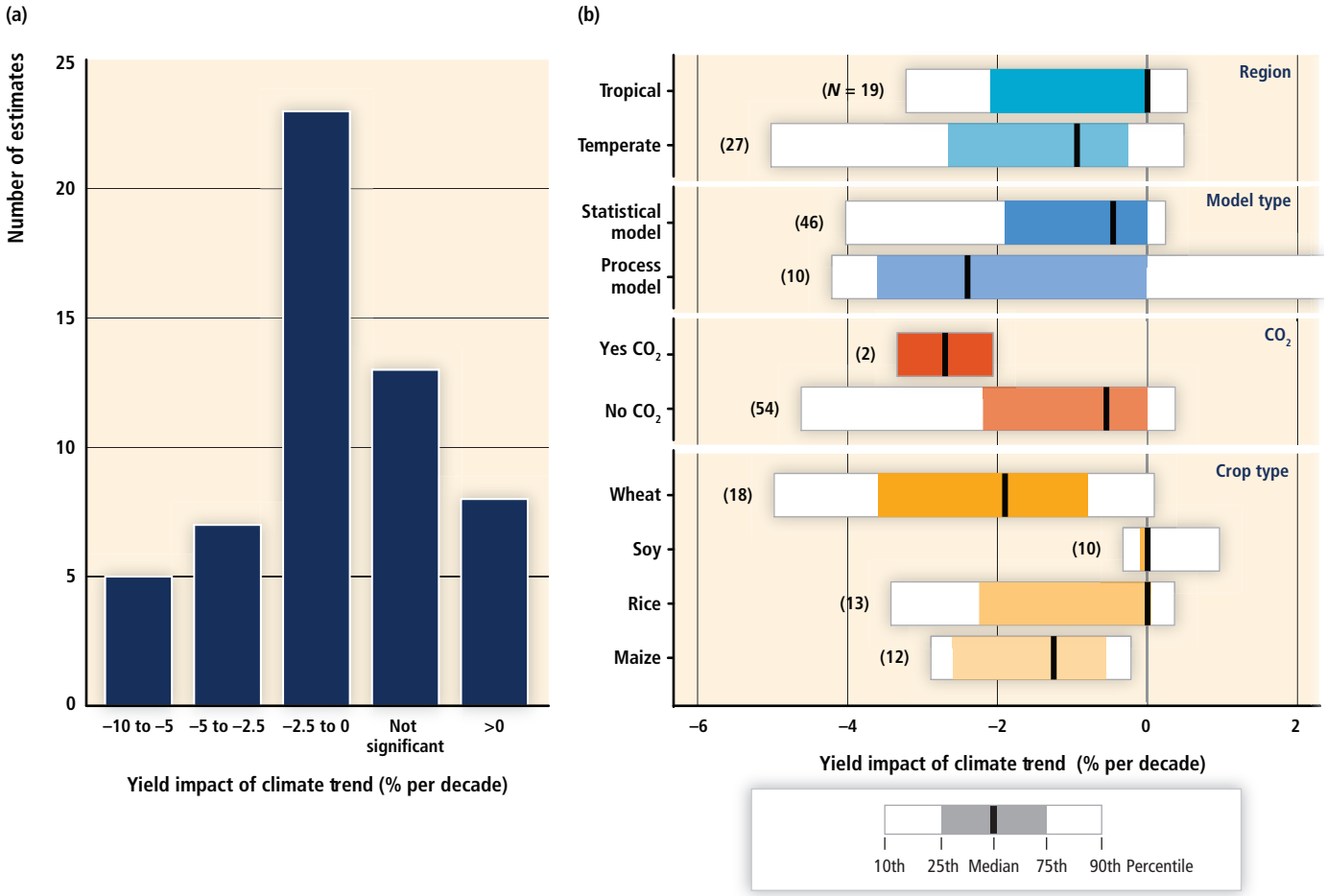

Figure 7-2 | Summary of estimates of the impact of recent climate trends on yields for four major crops. Studies were taken from the peer-reviewed literature and used different methods (i.e., physiological process-based crop models or statistical models), spatial scales (stations, provinces, countries, or global), and time periods (median length of 29 years). Some included effects of positive carbon dioxide (CO_2) trends (Section 7.3.2.1.2) but most did not. (a) Number of estimates with different level of impact (% yield per decade). (b) Boxplot of estimates separated by temperate vs. tropical regions, modeling approach (process-based vs. statistical), whether CO_2 effects were included, and crop. Boxplots indicate the median (vertical line), 25th to 75th percentiles (colored box), and 10th to 90th percentiles (white box) for estimated impacts in each category, and numbers in parentheses indicate the number of estimates. Studies were for China (Tao et al., 2006, 2008a, 2012; Wang et al., 2008; You et al., 2009; Chen et al., 2010), India (Pathak et al., 2003; Auffhammer et al., 2012), USA (Kucharik and Serbin, 2008), Mexico (Lobell et al., 2005), France (Brisson et al., 2010; Licker et al., 2013), Scotland (Gregory and Marshall, 2012), Australia (Ludwig et al., 2009), Russia (Licker et al., 2013), and some studies for multiple countries or global aggregates (Lobell and Field, 2007; Welch et al., 2010; Lobell et al., 2011a). Values from all studies were converted to percentage yield change per decade. Each study received equal weighting as insufficient information was available to judge the uncertainties of each estimate.

the changes in climate conditions are attributable to anthropogenic activity (WGI AR5 Chapter 10). Similarly, most crop studies have focused on the past few decades, a time scale shorter than most attribution studies for climate. However, some focused on continental or global scales (Lobell and Field, 2007; You et al., 2009; Lobell et al., 2011a), at which trends in several climatic variables, including average summer temperatures, have been attributed to anthropogenic activity. In particular, global temperature trends over the past few decades are attributable to human activity (WGI AR5 Chapter 10), and the studies discussed above indicate that this warming has had significant impacts on global yield trends of some crops.

In general, little work in food production or food security research has focused on determining whether climate trends affecting agriculture can be attributed to anthropogenic influence on the climate system. However, as the field of climate detection and attribution proceeds to finer spatial and temporal scales, and as agricultural modeling studies expand to broader scales, there should be many opportunities to link climate and crop studies in the next few years. Importantly, climate attribution is increasingly documented not only for measures of average conditions over growing seasons, but also for extremes. For instance, Min et al. (2011) attributed changes in rainfall extremes for 1951–1999 to anthropogenic activity, and these are widely acknowledged as important to cropping systems (Rosenzweig et al., 2002). Frost damage is an important constraint on crop growth in many crops, including for various high-value crops, and significant reductions in frost occurrence since 1961 have been observed and attributed to greenhouse gas (GHG) emissions in nearly every region of the world (Zwiers et al., 2011; IPCC, 2012).

Increased frequency of unusually hot nights since 1961 are also attributable to human activity in most regions (WGI AR5 Chapter 10). These events are damaging to most crops, an effect that has been observed most commonly for rice yields (Peng et al., 2004; Wassmann

et al., 2009; Welch et al., 2010) as well as rice quality (Okada et al., 2011). Extremely high daytime temperatures are also damaging and occasionally lethal to crops (Porter and Gawith, 1999; Schlenker and Roberts, 2009), and trends at the global scale in annual maximum daytime temperatures since 1961 have been attributed to GHG emissions (Zwiers et al., 2011). At regional and local scales, however, trends in daytime maximum are harder to attribute to GHG emissions because of the prominent role of soil moisture and clouds in driving these trends (Christidis et al., 2005; Zwiers et al., 2011).

In addition to effects of changes in climatic conditions, there are clear effects of changes in atmospheric composition on crops. Increase of atmospheric CO_2 by greater than 100 ppm since preindustrial times has *virtually certainly* enhanced water use efficiency and yields, especially for C_3 crops such as wheat and rice, although these benefits played a minor role in driving overall yield trends (Amthor, 2001; McGrath and Lobell, 2011).

Emissions of CO_2 often are accompanied by ozone (O_3) precursors that have driven a rise in tropospheric O_3 that harms crop yields (Morgan et al., 2006; Mills et al., 2007; Section 7.3.2.1.2). Elevated O_3 since preindustrial times has *very likely* suppressed global production of major crops compared to what they would have been without O_3 increases, with estimated losses of roughly 10% for wheat and soybean and 3 to 5% for maize and rice (Van Dingenen et al., 2009). Impacts are most severe over India and China (Van Dingenen et al., 2009; Avnery et al. 2011a,b), but are also evident for soybean and maize in the USA (Fishman et al., 2010).

7.2.1.2. Fisheries Production

The global average consumption of fish and other products from fisheries and aquaculture in 2010 was 18.6 kg per person per year, derived from a total production of 148.5 million tonnes, of which 86% was used for direct human consumption. The total production arose from contributions of 77.4 and 11.2 million tonnes respectively from marine and inland capture fisheries, and 18.1 and 41.7 million tonnes respectively from marine and freshwater aquaculture (FAO, 2012). Fisheries make particular contributions to food security and more than 90% of the people engaged in the sector are employed in small-scale fisheries, many of whom are found in the poorer countries of the world (Cochrane et al., 2011). The detection and attribution of impacts are as confounded in inland and marine fisheries as in terrestrial food production systems. Overfishing, habitat modification, pollution, and interannual to decadal climate variability can all have impacts that are difficult to separate from those directly attributable to climate change.

One of the best studied areas is the Northeast Atlantic, where the temperature has increased rapidly in recent decades, associated with a poleward shift in distribution of fish (Perry et al., 2005; Brander, 2007; Cheung et al., 2010, 2013). There is *high confidence* in observations of increasing abundance of fish species in the northern extent of their ranges while decreases in abundance have occurred in the southern part (Section 30.5.1.1.1). These trends will have mixed implications for fisheries and aquaculture with some commercial species negatively and others positively affected (Cook and Heath, 2005). There is a similar well-documented example in the oceans off southeast Australia with large warming trends associated with more southward incursion of the Eastern Australian Current, resulting in southward migration of marine species into the oceans around eastern Tasmania (*robust evidence*, *high agreement*; Last et al., 2011).

As a further example, coral reef ecosystems provide food and other resources to more than 500 million people and with an annual value of US$5 billion or more (Munday et al., 2008; Hoegh-Guldberg, 2011). More than 60% of coral reefs are considered to be under immediate threat of damage from a range of local threats, of which overfishing is the most serious (Burke et al., 2011; see also Box CC-CR) and the percentage under threat rises to approximately 75% when the effect of rising ocean temperatures is added to these local impacts (Burke et al., 2011). Wilson et al. (2006) demonstrated that declines in coral reef cover typically led to declines in abundance of the majority of fish species associated with coral reefs. There is *high confidence* that the availability of fish and invertebrate species associated with coral reefs that are important in many tropical coastal fisheries is *very likely* to be reduced (Section 30.6.2.1.2). Other examples around the world are described in Section 30.5.1.1.1.

These changes are impacting marine fisheries: a recent study that examined the composition of global fisheries catches according to the inferred temperature preferences of the species caught in fisheries found that there had been changes in the species composition of marine capture fisheries catches and that these were significantly related to changes in ocean temperatures (Cheung et al. 2013; Section 6.4.1.1). These authors noted that the relative contribution to catches by warmer water species had increased at higher latitudes while the contributions of subtropical species had decreased in the tropics. These changes have negative implications for coastal fisheries in tropical developing countries, which tend to be particularly vulnerable to climate change (Cheung et al., 2013; Sections 6.4.3, 7.5.1.1.2).

There is considerably less information available on climate change impacts on fisheries and fishery resources in freshwater systems and aquaculture. Considerable attention has been given to the impacts of climate change in some African lakes but with mixed interpretations (Section 22.3.3.1.4). There is evidence that increasing temperature has reduced the primary productivity of Lake Tanganyika in East Africa and a study by O'Reilly et al. (2003) estimated that this would have led to a decrease of approximately 30% in fish yields. However, Sarvala et al. (2006) disagreed and concluded that observed decreases in the fish catches could be explained by changed fishery practices. There has been a similar difference of opinion for Lake Kariba, where Ndebele-Murisa et al. (2011) argued that a reduction in fisheries productivity had been caused by climate change while Marshall (2012) argued that the declines in fish catches can only have been caused by fishing. There is *medium confidence* that, in India, changes in a number of climate variables including an increase in air temperature, regional monsoon variation, and a regional increase in incidence of severe storms have led to changes in species composition in the River Ganga and to have reduced the availability of fish spawn for aquaculture in the river Ganga while having positive impacts on aquaculture on the plains through bringing forward and extending the breeding period of the majors carps (Vass et al., 2009).

Frequently Asked Questions

FAQ 7.1 | What factors determine food security and does low food production necessarily lead to food insecurity?

Observed data and many studies indicate that a warming climate has a negative effect on crop production and generally reduces yields of staple cereals such as wheat, rice, and maize, which, however, differ between regions and latitudes. Elevated CO_2 could benefit crops yields in the short term by increasing photosynthesis rates; however, there is big uncertainty in the magnitude of the CO_2 effect and the significance of interactions with other factors. Climate change will affect fisheries and aquaculture through gradual warming, ocean acidification, and changes in the frequency, intensity, and location of extreme events. Other aspects of the food chain are also sensitive to climate but such impacts are much less well known. Climate-related disasters are among the main drivers of food insecurity, both in the aftermath of a disaster and in the long run. Drought is a major driver of food insecurity, and contributes to a negative impact on nutrition. Floods and tropical storms also affect food security by destroying livelihood assets. The relationship between climate change and food production depends to a large degree on when and which adaptation actions are taken. Other links in the food chain from production to consumption are sensitive to climate but such impacts are much less well known.

7.2.1.3. Livestock Production

In comparison to crop and fish production, considerably less work has been published on observed impacts for other food production systems, such as livestock or aquaculture, and to our knowledge nothing has been published for hunting or collection of wild foods other than for capture fisheries. The relative lack of evidence reflects a lack of study in this topic, but not necessarily a lack of real-world impacts of observed climate trends. A study of blue-tongue virus, an important ruminant disease, evaluated the effects of past and future climate trends on transmission risk, and concluded that climate changes have facilitated the recent and rapid spread of the virus into Europe (Guis et al., 2012). Ticks that carry zoonotic diseases have also *likely* changed distribution as a consequence of past climate trends (Section 23.4.2).

7.2.2. Food Security and Food Prices

Food production is an important aspect of food security (Section 7.1), and the evidence that climate change has affected food production implies some effect on food security. Yet quantifying this effect is an extremely difficult task, requiring assumptions about the many non-climate factors that interact with climate to determine food security. There is thus limited direct evidence that unambiguously links climate change to impacts on food security.

One important aspect of food security is the prices of internationally traded food commodities (Section 7.1.3). These prices reflect the overall balance of supply and demand, and the accessibility of food for consumers integrated with regional to global markets. Although food prices gradually declined for most of the 20th century (FAO, 2009b) since AR4 there have been several periods of rapid increases in international food prices (Figure 7-3). A major factor in recent price changes has been increased crop demand, notably via increased use in biofuel production related both to energy policy mandates and oil price fluctuations (Roberts and Schlenker, 2010; Mueller et al., 2011; Wright, 2011). Yet fluctuations and trends in food production are also widely believed to have played a role in recent price changes, with recent price spikes often following climate extremes in major producers (Figure 7-3). Moreover, some of these extreme events have become more likely as a result of climate trends (Table 18-3). Domestic policy reactions can also amplify international price responses to weather events, as was the case with export bans announced by several countries since 2007 (FAO, 2008). In a study of global production responses to climate trends (Lobell et al., 2011a) estimated a price increase of 19% due to the impacts of temperature and precipitation trends on supply, or an increase of 6% once the beneficial yield effects of increased CO_2 over the study period were considered. Because the price models were developed for a period ending in 2003, these estimates do not account for the policy responses witnessed in recent years which have amplified the price responses to weather.

7.3. Assessing Impacts, Vulnerabilities, and Risks

7.3.1. Methods and Associated Uncertainties

7.3.1.1. Assessing Impacts

Methods developed or extended since AR4 have resulted in more robust statements on climate impacts, both in the literature and in Section 7.3.2. Two particular areas, which are explored below, are improved quantification and presentation of uncertainty; and greater use of historical empirical evidence of the relationship between climate and food production.

The methods used for field and controlled environment experiments remain similar to those at the time of AR4. There has been a greater use of remote sensing and geographic information systems for assessing temporal and spatial changes in land use, particularly in agricultural land use for assessment of food security status (Thenkabail et al., 2009;

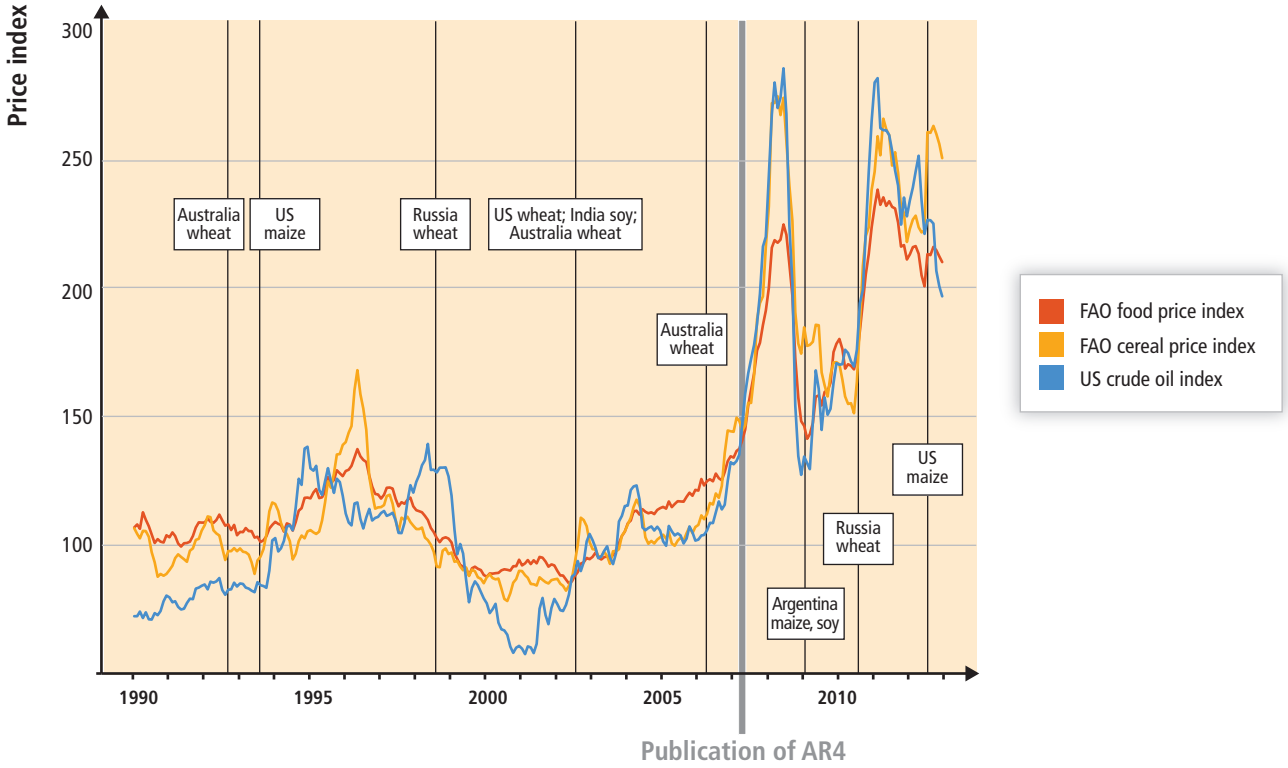

Figure 7-3 | Since the AR4, international food prices have reversed historical downward trend. The plot shows the history of FAO food and cereal price indices (composite measures of food prices), with vertical lines indicating events when a top five producer of a crop had yields 25% below trend line (indicative of a seasonal climate extreme). Australia is included despite not being a top five producer, because it is an important exporter and the drops were 40% or more below trend line. Prices may have become more sensitive to weather-related supply shortfalls in recent years. At the same time, food prices are increasingly associated with the price of crude oil (blue line), making attribution of price changes to climate difficult. Thus, there is clear evidence since AR4 that prices can rise rapidly, but the role of weather in these increases remains unclear. All indices are expressed as percentage of 2002–2004 averages. Food price and crop yield data from FAO (http://www.fao.org/worldfoodsituation/foodpricesindex and http://faostat.fao.org/) and oil price data from http://www.eia.gov.

Fishman et al., 2010; Goswami et al., 2012). There has also been an increase in the number of Free Air Concentration Enrichment (FACE) studies that examine O_3 instead of, or in addition to, CO_2. In agriculture, FACE experiments have been used for assessing impacts of atmospheric CO_2 on grain yield, quality characteristics of important crops (Erbs et al., 2010), elemental composition (Fernando et al., 2012), and diseases (Chakraborty et al., 2011; Eastburn et al., 2011). A number of meta-analyses of experimental studies, in particular FACE studies, have been made since AR4. However, debate continues on the disparities between results from FACE experiments and non-FACE experiments, such as in open-top chambers or greenhouses. As reported in AR4, FACE studies tend to show lower elevated CO_2 responses than non-FACE studies. Although some authors have claimed that the results of the two are statistically indistinct, others have argued that the results are similar only when the FACE experiments are grown under considerably more water stress than non-FACE experiments (Ainsworth et al., 2008; Kimball, 2010). Hence comparisons between different methodologies must take care to control for differences in water availability and microclimate. Another reason for differences between experiments may be differences in the temporal variance of CO_2, that is, whether concentrations are fluctuating or constant (Bunce, 2012). Unfortunately, the FACE experiments are carried out mostly in the USA and in China, and thus limited to specific environmental conditions, which do not fully reflect tropical or subtropical conditions, where CO_2 and soil nutrient interactions could lead to large differences in photosynthesis rate, water use, and yield. Also, the number of FACE studies is still quite low, which limits statistical power when evaluating the average yield effects of elevated CO_2 or interactions with temperature and moisture (Section 7.3.2).

Numerical simulation models can be used to investigate a larger number of possible environmental and management conditions than possible via physical experiments. This, in turn, enables a broader range of statements regarding the possible response of food production systems to climate variability and change. Previous assessment reports have documented new knowledge resulting from numerical simulation of the response of food production to climate change. AR4 noted the increasing number of regional studies, which is a trend that has continued to date (Craufurd et al., 2013; Zhu et al., 2013). Since AR4, crop models have been used to examine a large number of management and environmental conditions, such as interactions among various components of food production systems (Lenz-Wiedemann et al., 2010), determination of optimum crop management practices (Soltani and Hoogenboom, 2007), vulnerability and adaptability assessments (Sultana et al., 2009), evaluation of water consumption and water use efficiency (Kang et al., 2009; Mo et al., 2009), and fostering communication among scientists, managers, policymakers, and planners.

The trend toward quantification of uncertainty in both climate and its impacts has continued since AR4. Novel developments include methodologies to assess the impact of climate model error on projected

agricultural output, particularly for crops (Ramirez-Villegas et al., 2013, Watson and Challinor, 2013). Models that integrate crop growth models as part of broader land surface and earth systems models (Bondeau et al., 2007; Osborne et al., 2007) are also increasingly common. Ensemble techniques for climate impacts, which were in their infancy at AR4, now include the use of Bayesian methods to constrain crop model parameters (Tao et al., 2008b, 2009a; Iizumi et al., 2009). It is also increasingly common to assess both biophysical and socioeconomic drivers of crop productivity within the same study (Fraser et al., 2008; Reidsma et al., 2009; Challinor et al., 2010; Tao et al., 2011b). Finally, an important recent development is the systematic comparison of results from different modeling and experimental approaches for providing insights into model uncertainties as well as to develop risk management (Challinor and Wheeler, 2008; Kang et al., 2009; Schlenker and Lobell, 2010; Rosenzweig et al., 2013, 2014).

Increased quantification of uncertainty can lead to clear statements regarding climate impacts. Studies with different methods have been shown to produce convergent results for some crops and locations (Challinor et al., 2009; *medium evidence*, *medium agreement*). The methods used to describe uncertainty have also improved since AR4. The projected range of global and local temperature changes can be described by quantifying uncertainty in the temporal dimension, rather than that in temperature itself (Joshi et al., 2011), and a similar approach can be used for crop yield (Figure 7-5). Descriptions of uncertainty that present key processes and trade-offs, rather than ranges of outcome variables, have also proved to be useful tools for understanding future impacts (Thornton et al., 2009a; Hawkins et al., 2012; Ruane et al., 2013). Section 7.3.2 reviews the results of such studies.

A considerable body of work since AR4 has used extensive data sets of country-, regional-, and farm-level crop yield together with observed and/or simulated weather time series to assess the sensitivity of food production to weather and climate (Tao et al., 2009a, 2011). Statistical models offer a complement to more process-based model approaches, some of which require many assumptions about soil and management practices. Process-based models, which extrapolate based on measured interactions and mechanisms, can be used to develop a causal understanding of the empirically determined relationships in statistical models (cf. Schlenker and Roberts, 2009; Lobell et al., 2013a). Although statistical models forfeit some of the process knowledge embedded in other approaches, they can often reproduce the behavior of other models (Iglesias et al., 2000; Lobell and Burke, 2010) and can leverage within one study a growing availability of crop and weather data (Welch et al., 2010; Lobell et al., 2011b). However, statistical models usually exclude the direct impact of elevated CO_2, making multi-decadal prediction problematic. In determining future trends, crop models of all types can extrapolate only based on historically determined relationships. Agro-climatic indices provide an alternative to crop models that avoid various assumptions by developing metrics, rather than providing yield predictions per se (Trnka et al., 2011). However, correlations between climate or associated indices and yield are not always statistically significant.

The robustness of crop model results depends on data quality, model skill prediction, and model complexity (Bellocchi et al., 2010). Modeling and experiments are each subject to their own uncertainties. Measurement uncertainty is a feature of field and controlled environment experiments. For example, interactions among CO_2 fertilization, temperature, soil nutrients, O_3, pests, and weeds are not well understood (Soussana et al., 2010) and therefore most crop models do not include all of these effects, or broader issues of water availability, such as competition for water between industry and households (Piao et al., 2010). There are also uncertainties associated with generalizing the results of field experiments, as each one has been conducted relatively few times under a relatively small range of environmental and management conditions, and for a limited number of genotypes. This limits breadth of applicability both through limited sample size and limited representation of the diversity of genotypic responses to environment (Craufurd et al., 2013). For example, yield increases normalized by increase in CO_2 have been found to vary between zero and more than 30% among crop varieties (Tausz et al., 2011).

Uncertainty in climate simulation is generally larger than, or sometimes comparable to, the uncertainty in crop simulation using a single crop model (Iizumi et al., 2011), although temperature-driven processes in crop models have been shown to dominate the causes of uncertainty (Koehler et al., 2013). There is significant uncertainty in agricultural simulation arising from climate model error. Since AR4 the choice of method for General Circulation Model (GCM) bias correction has been identified as a significant source of uncertainty (Hawkins et al., 2012). There is also a contribution to uncertainty in crop model output from yield measurement error, through the calibration procedure. Yield measurements rarely have associated error bars to give an indication of accuracy. Greater access to accurate regional-scale crop yield data can lead to decreased uncertainty in projected yields (Watson and Challinor, 2013).

The use of multiple crop models in impacts studies is relatively rare. Field-scale historical model intercomparisons have shown variations in the simulation of mean yield and above-ground biomass of more than 60% (Palosuo et al., 2011). Early results from impacts studies with multiple crop models suggest that the crop model uncertainty can be larger than that caused by GCMs, due in particular to high temperature and temperature-by-CO_2 interactions (Asseng et al., 2013). However, in contrast to absolute values, yield changes can be consistent across crop models (Olesen et al., 2007). Given these different strengths and weaknesses, and associated dependencies, it is critical that both experimental and modeling lines of evidence, and their uncertainties, are examined carefully when drawing conclusions regarding impacts, vulnerabilities, and risks. This approach to assessment is applied to each of the topics described in the rest of the chapter.

The methods used for assessing impacts, vulnerabilities, and risks in fisheries and aquaculture face the constraint that meaningful controlled experiments are usually not practical for fisheries in large rivers, lakes, and marine environments because of the typical open and connected nature of these ecosystems. Experimentation has been used to examine responses to impacts at the scale of individual species, for example, to demonstrate the impacts of high atmospheric CO_2 in reducing coral calcification and growth (Hoegh-Guldberg et al., 2007) and to study the temperature tolerances of different cultured species (Ficke et al., 2007; De Silva and Soto, 2009). The far more common approach, however, is the empirical analysis of data collected in the field. This has been used

to examine the effect of climate-related factors on recruitment to a population, growth, and population production of specific species, for example (Brander, 2010; see also Chapters 6 and 30). Different modeling approaches have also been used to integrate available information and assess the impacts of climate change on ecosystems and fish production at scales from national to global (Cheung et al., 2010; Fulton, 2011; Merino et al., 2012; see also Section 6.5). Efforts to assess the vulnerability of those dependent on fisheries and aquaculture have increased in recent years and range from studies that use available information on exposure, sensitivity, and adaptive capacity to provide an index of vulnerability (Allison et al., 2009; Cinner at al., 2012) to more detailed social and economic studies focused on particular communities or localities (Daw et al., 2009).

7.3.1.2. Treatment of Adaptation in Impacts Studies

Adaptation occurs on a range of time scales and by a range of actors. Incremental adaptation, such as a change in crop management, can occur relatively autonomously within farming systems. It is the type of adaptation most commonly assessed in the impacts literature, and it is the only form of adaptation discussed in Sections 7.3 and 7.4. Systemic and transformational adaptations are discussed in Section 7.5. Methods exist to examine impacts and adaptation together in the context of non-climatic drivers (Mandryk et al., 2012), but conclusions are difficult to generalize.

7.3.2. Sensitivity of Food Production to Weather and Climate

7.3.2.1. Cereals and Oilseeds

7.3.2.1.1. Mean and extremes of temperature and precipitation

Both statistical and process-based models have been used widely since AR4 to assess the response of crop yield to temperature. Model results confirm the importance of known key physiological processes, such as the shortening of the time to maturity of a crop with increasing mean temperature (Iqbal et al., 2009), decline in grain set when high temperatures occur during flowering (Moriondo et al., 2011), and increased water stress at high temperatures throughout the growing cycle (Lobell et al., 2013a). Temperature responses are generally well understood for temperatures up to the optimum temperature for crop development. The impacts of prolonged periods of temperatures beyond the optimum for development are not as well understood (Craufurd and Wheeler, 2009). For example, temperatures above 32-34°C after flowering appear to speed senescence rapidly in wheat (Asseng et al., 2011; Lobell et al., 2012), but many crop models do not represent this process (Sanchez et al., 2014). Crop models can be used to quantify abiotic stresses such as these, although only by hypothesizing that the functional responses to weather derived from experiments are valid at regional scales. Thus, although many fundamental biophysical processes are understood at the plant or field scale, it remains difficult to quantify the extent to which these mechanisms are responsible for the observed regional-scale relationships between crop yield and weather. Despite these particular areas where specific understanding is lacking, the evidence from regional-scale statistical analyses (Schlenker and Roberts, 2009) and process-based models shows clear negative impacts of temperatures above 30°C to 34°C on crop yields (depending on the crop and region) (*high evidence*, *high agreement*).

The overall relationship between weather and yields is often crop and region specific, depending on differences in baseline climate, management and soil, and the duration and timing of crop exposure to various conditions. For example, rice yields in China have been found to be positively correlated with temperature in some regions and negatively correlated in others (Zhang et al., 2008, 2010). The trade-offs that occur in determining yield are therefore region-specific. This difference may be due to positive correlation between temperature and solar radiation in the former case, and negative correlation between temperature and water stress in the latter case. Similarly, although studies consistently show spikelet sterility in rice for daytime temperatures exceeding 33°C (Jadadish et al., 2007; Wassmann et al., 2009), some statistical studies find a positive effect of daytime warming on yields because these extremes are not reached frequently enough to affect yields (Welch et al., 2010). Responses to temperature may vary according whether yields are limited by low or high temperatures. However, there is evidence that high temperatures will limit future yields even in cool environments (Semenov et al., 2012; Teixeira et al., 2013).

The relative importance of temperature and water stress for crop productivity can be assessed using models, and can vary according to the criteria used for assessment (Challinor et al., 2010). There are also some cases where the sign of a correlation depends on the direction of the change. For example, Thornton et al. (2009b) found that the response of crop yields to climate change in the drylands of East Africa is insensitive to increases in rainfall, as wetter climates are associated with warmer temperatures that act to reduce yields. Because precipitation exhibits more spatial variability than temperature, temporal variations in the spatial average of precipitation tend to diminish as the spatial domain widens. As a result, precipitation becomes less important as a predictor of crop yields at broad scales (Lobell and Field, 2007; Li et al., 2010). Similarly, projected changes in precipitation from climate models tend to be more spatially variable than temperature, leading to the greater importance of projected temperatures as the spatial scale of analysis grows wider (Lobell and Burke, 2008). There is also evidence that where irrigation increases over time the influence of temperature on yields starts to dominate over that of precipitation (Hawkins et al., 2012). The impact of drought on crop yield is a more common topic of research than the impact of floods.

Analysis of 66 yield impact studies for major cereals, including both pre- and post-AR4 contributions, gives broadly similar results to AR4 (Figure 7-4). Figure 7-4 shows that yields of maize and wheat begin to decline with 1°C to 2°C of local warming in the tropics. Temperate maize and tropical rice yields are less clearly affected at these temperatures, but significantly affected with warming of 3°C to 5°C. These data confirm AR4 findings that even slight warming will decrease yields in low-latitude regions (medium evidence, high agreement). However, although AR4 had few indications of yield reductions at less than 2°C of local warming, the new analysis has, in the absence of incremental adaptation, more yield decreases than increases at all temperatures. Hence, although AR4 concluded with *medium confidence* that in mid- to high-latitude

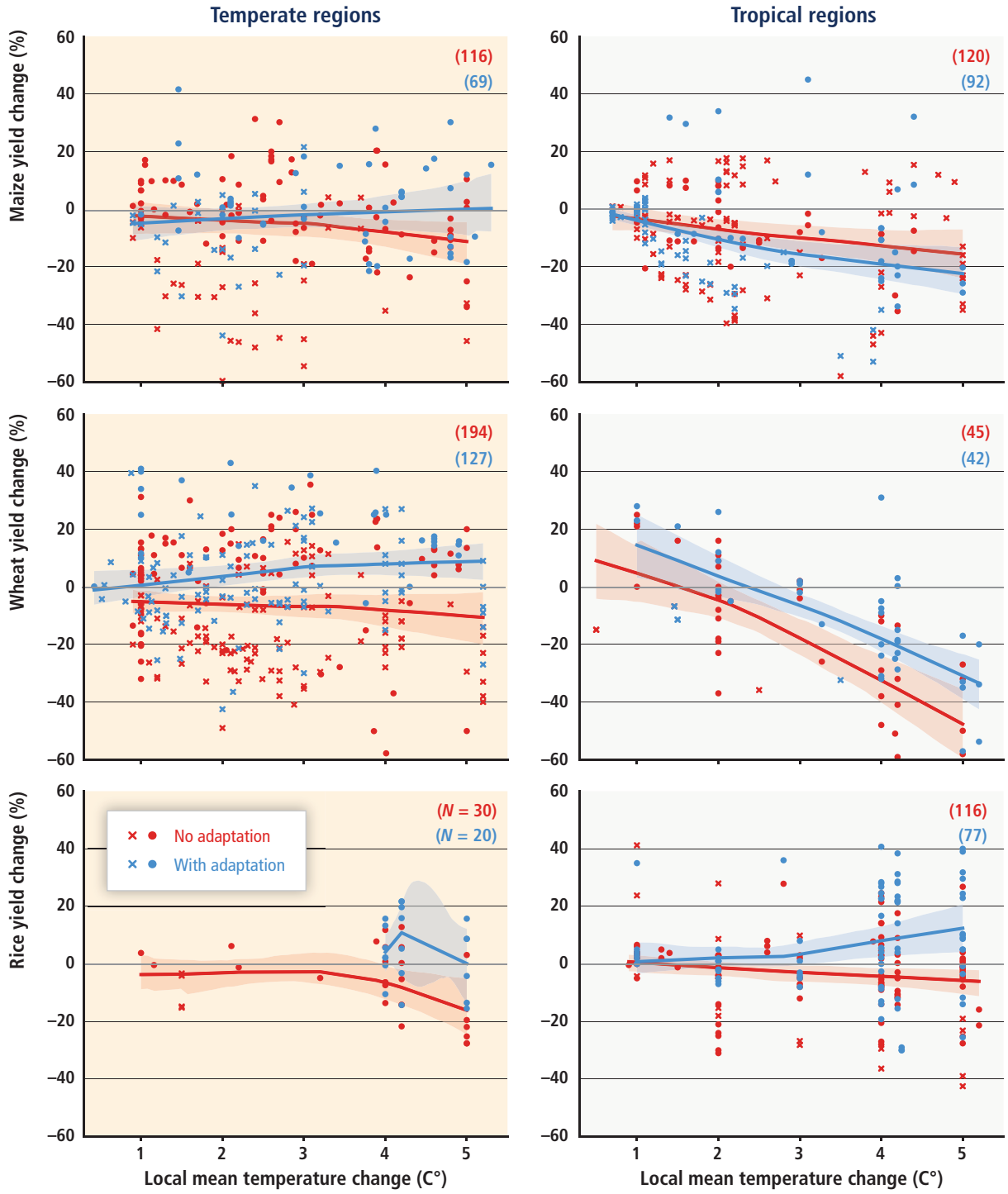

Figure 7-4 | Percentage simulated yield change as a function of local temperature change for the three major crops and for temperate and tropical regions. Dots indicate where a known change in atmospheric CO_2 was used in the study; remaining data are indicated by x. Note that differences in yield value between these symbols do not measure the CO_2 fertilization effect, as changes in other factors such as precipitation may be different between studies. Non-parametric regressions (LOESS, span = 1 and degree = 1) of subsets of these data were made 500 times. These bootstrap samples are indicated by shaded bands at the 95% confidence interval. Regressions are separated according to the presence (blue) or absence (red) of simple agronomic adaptation (Table 7-2). In the case of tropical maize, the central regression for absence of adaptation is slightly higher than that with adaptation. This is due to asymmetry in the data—not all studies compare adaptated and non-adapted crops. Figure 7-8 presents a pairwise adaptation comparison. Note that four of the 1048 data points across all six panels are outside the yield change range shown. These were omitted for clarity. Some of the studies have associated temporal baselines, with center points typically between 1970 and 2005. Note that local warming in cropping regions generally exceeds global mean warming (Figure 21-4). Data are taken from a review of literature: Rosenzweig and Parry, 1994; Karim et al., 1996; El-Shaher et al., 1997; Kapetanaki and Rosenzweig, 1997; Lal et al., 1998; Moya et al., 1998; Winters et al., 1998; Yates and Strzepek, 1998; Alexandrov, 1999; Kaiser, 1999; Reyenga et al., 1999; Alexandrov and Hoogenboom, 2000; Southworth et al., 2000; Tubiello et al., 2000; DeJong et al., 2001; Izaurralde et al., 2001; Aggarwal and Mall, 2002; Abou-Hadid, 2006; Alexandrov et al., 2002; Corobov, 2002; Chipanshi et al., 2003; Easterling et al., 2003; Jones and Thornton, 2003; Luo et al., 2003; Matthews and Wassmann, 2003; Droogers, 2004; Howden and Jones, 2004; Butt et al., 2005; Erda et al., 2005; Ewert et al., 2005; Gbetibouo and Hassan, 2005; Izaurralde et al., 2005; Porter and Semenov, 2005; Sands and Edmonds, 2005; Thomson et al., 2005; Xiao et al., 2005; Zhang and Liu, 2005; Zhao et al., 2005; Abraha and Savage, 2006; Brassard and Singh, 2007, 2008; Krishnan et al., 2007; Lobell and Ortiz-Monasterio, 2007; Xiong et al., 2007; Tingem et al., 2008; Walker and Schulze, 2008; El Maayar et al., 2009; Schlenker and Roberts, 2009; Thornton et al., 2009a, 2010, 2011; Tingem and Rivington, 2009; Byjesh et al., 2010; Chhetri et al., 2010; Liu et al., 2010; Piao et al., 2010; Tan et al., 2010; Tao and Zhang, 2010, 2011a,b; Arndt et al., 2011; Deryng et al., 2011; Iqbal et al., 2011; Lal, 2011; Li et al., 2011; Rowhanji et al., 2011; Shuang-He et al., 2011; Osborne et al., 2013.

regions moderate warming will raise crop yields, new knowledge suggests that temperate wheat yield decreases are *about as likely as not* for moderate warming. A recent global crop model intercomparison for rice, wheat, and maize shows similar results to those presented here, although with less impacts on temperate rice yields (Rosenzweig et al., 2013, 2014). That study also showed that crop models without explicit nitrogen stress fail to capture the expected response.

Quantitative assessments of yield changes can be found in Section 7.4. Across the globe, regional variability, which has not been summarized in meta-analyses except in contributing to the spread of data (Figure 7-4), will be important in determining how climate change affects particular agricultural systems.

7.3.2.1.2. Impact of carbon dioxide and ozone

There is further observational evidence since AR4 that response to a change in CO_2 depends on plant type: C_3 or C_4 (DaMatta et al., 2010). The effect of increase in CO_2 concentration tends to be higher in C_3 plants (wheat, rice, cotton, soybean, sugar beets, and potatoes) than in C_4 plants (corn, sorghum, sugarcane), because photosynthesis rates in C_4 crops are less responsive to increases in ambient CO_2 (Leakey, 2009). The highest fertilization responses have been observed in tuber crops, which have large capacity to store extra carbohydrates in belowground organs (Fleisher et al., 2008; Högy and Fangmeier, 2009). There is observational evidence, new since AR4, that the response of crops to CO_2 is genotype specific (Ziska et al., 2012). For example, yield enhancement at 200 ppm additional CO_2 ranged from 3 to 36% among rice cultivars (Hasegawa et al., 2013).

FACE studies have shown that the impact of elevated CO_2 varies according to temperature and availability of water and nutrients, although the strong geographical bias of FACE studies toward temperate zones limits the strength of this evidence. FACE studies have shown that yield enhancement by elevated CO_2 is limited under both low (Shimono et al., 2008; Hasegawa et al., 2013) and high temperature. Theory suggests that water-stressed crops will respond more strongly to elevated CO_2 than well-watered crops, because of CO_2-induced increases in stomatal resistance. This suggests that rain-fed cropping systems will benefit more from elevated CO_2 than irrigated systems.

Both the Third Assessment Report (TAR) and AR4 cited the expectation that rain-fed systems benefit more from elevated CO_2 than systems under wetter conditions. New evidence based on historical observations supports this notion by demonstrating that the rate of yield gains in rain-fed systems is higher in dry years than in wet years (McGrath and Lobell, 2011). However, this response is not seen consistently across models and FACE meta-analyses, and there is some suggestion that the relationship between water stress and assimilation may vary with spatial scale, with canopy analyses showing a reversal of the expected leaf-level dry versus wet signal (Challinor and Wheeler, 2008).

O_3 in the stratosphere provides protection from lethal short-wave solar ultraviolet radiation, but in the troposphere it is a phytotoxic air pollutant. The global background concentration of O_3 has increased since the preindustrial era due to anthropogenic emission of its precursors (carbon monoxide, volatile organic compounds, and oxides of nitrogen), by vehicles, power plants, biomass burning, and other sources of combustion. Like CO_2, O_3 is taken up by green leaves through stomata during photosynthesis but, unlike CO_2, its concentration is significantly variable depending on geographic location, elevation, and extent of anthropogenic sources. Being a powerful oxidant, O_3 and its secondary by-products damage vegetation by reducing photosynthesis and other important physiological functions (Mills et al., 2009; Ainsworth and McGrath, 2010). This results in stunted crop plants, inferior crop quality, and decreased yields (Booker et al., 2009; Fuhrer, 2009; Vandermeiren et al., 2009; Pleijel and Uddling, 2012) and poses a growing threat to global food security (*robust evidence*, *high agreement*).

The literature published since AR4 further corroborates the negative impacts of increasing concentrations of surface O_3 on yield at global (Van Dingenen et al., 2009; Avnery et al., 2011a,b; Teixeira et al., 2011) and regional scales (Northern Hemisphere: Hollaway et al., 2011; USA: Emberson et al., 2009; Fuhrer, 2009; Fishman et al., 2010; India: Roy et al., 2009; Rai et al., 2010; Sarkar and Agrawal, 2010; China: Wang et al., 2007, 2011; Piao et al., 2010; Bangladesh: Akhtar et al., 2010; Europe: Hayes et al., 2007; Fuhrer, 2009; Vandermeiren et al., 2009). Global estimates of yield losses due to increased O_3 in soybean, wheat, and maize in 2000 ranged from 8.5 to 14%, 3.9 to 15%, and 2.2 to 5.5% respectively, amounting to economic losses of US$11 to 18 billion (Avnery et al., 2011a). O_3 may have a direct effect on reproductive process, leading to reduced seed and fruit development and abortion of developing fruit (*robust evidence*, *high agreement*; Royal Society, 2008).

The interactive effects of O_3 with other environmental factors such as CO_2, temperature, moisture, and light, are important but not well understood. Generally, the ambient and increasing concentrations of O_3 and CO_2 individually exert counteractive effects on C_3 plants (Tianhong et al., 2005; Ainsworth et al., 2008; Gillespie et al., 2012), but their interactive effect may compensate for each other (Ainsworth et al., 2008; Taub et al., 2008; Gillespie et al., 2012). However, the losses might be greater when elevated O_3 combines with high temperature (Long, 2012) particularly during grain filling of wheat, when elevated O_3 causes premature leaf senescence (Feng et al., 2008b, 2011). Periods of abundant radiation and adequate water supply are favorable for both agricultural production and the formation of surface O_3; thus, the effects of O_3 on crops can be difficult to detect (Long, 2012).

7.3.2.2. Other Crops

Earlier flowering and maturity have been observed (*robust evidence*, *high agreement*) worldwide in grapes (Duchêne et al., 2010; García-Mozo et al., 2010; Jorquera-Fontena and Orrego-Verdugo, 2010; Sadras and Petrie, 2011; Webb et al., 2011), apples (Fujisawa and Koyabashi, 2010; Grab and Craparo, 2011), and other perennial horticultural crops (Glenn et al., 2013). Cassava (also known as manioc) is an important source of food for many people in Africa and Latin America and recent studies suggest (*medium evidence*, *medium agreement*) that future climate should benefit its productivity as this crop is characterized by elevated optimum temperature for photosynthesis and growth, and a positive response to CO_2 increases (El-Sharkawy, 2012; Jarvis et al., 2012; Rosenthal and Ort, 2012).

7.3.2.3. Pests, Weeds, Diseases

As a worldwide average, yield loss in major crop species due to animal pests and (non-virus) pathogens, in the absence of any physical, biological, or chemical crop protection, has been estimated at 18% and 16%, respectively (Oerke, 2006), but weeds produce the highest potential loss (34%). Climate change will alter potential losses to many pests and diseases. Changes in temperature can result in geographic shifts through changes in seasonal extremes, and thus, for example, overwintering and summer survival. CO_2 and O_3 can either increase or decrease plant disease, and can exhibit important interactions (Chakraborty and Newton, 2011; Garrett et al., 2011), suggesting the need for system-specific risk assessment (Chakraborty et al., 2008; Eastburn et al., 2011). Interactions with landscape effects may be particularly important in forests and grasslands (Pautasso et al., 2010).

The rarity of long-term studies of plant diseases and pests is a problem for the evaluation of climate change effects, but there are some examples of the potential for such analyses. Ongoing wheat experiments at Rothamsted Research Station UK, maintained for more than 160 years, have revealed shifts in foliar wheat pathogens linked to rainfall, temperature, and sulfur dioxide (SO_2) emissions (Bearchell et al., 2005; Shaw et al., 2008). Wheat rust risk has been observed to respond to El Niño-Southern Oscillation (ENSO; Scherm and Yang, 1995). Over almost 7 decades, earlier and more frequent epidemics of potato late blight, and more frequent pesticide use, were observed in Finland, associated with changing climate conditions and lack of crop rotation (Hannukkala et al., 2007).

Changes in climate are expected to affect the geographic range of specific species of insects and diseases for a given crop growing region. For example, Cannon (1998) has suggested that migratory insects could colonize crops over a larger range in response to temperature increases, with subsequent reductions in yield. Climate change may also be a factor in extending the northward migration of agronomic and invasive weeds in North America (Ziska et al., 2011). Weed species also possess characteristics that are associated with long-distance seed dispersal, and it has been suggested (Hellman et al., 2008) that they may migrate rapidly with increasing surface temperatures. Predator and insect herbivores respond differently to increasing temperature, leading to possible reductions in insect predation and thus greater insect numbers. However, ecosystems are complex and insect and disease occurrence can go down as well as up. Overall, our ability to predict CO_2/climate change impacts on pathogen biology and subsequent changes on yield is limited because, with few exceptions (Savary et al., 2011), experimental data are not available and analyses focus on individual diseases rather than the complete set of important diseases (*medium evidence*, *medium agreement*).

Elevated CO_2 can reduce yield losses due to weeds for C_3 crops (soybean, wheat, and rice), as many agricultural weeds are C_4 species; and the C_3 pathway, in general, shows a stronger response to rising CO_2 levels. However, both C_3 and C_4 weed species occur in agriculture, and there is a wide range of responses among these species to recent and projected CO_2 levels (Ziska, 2010). For example, in the USA, every crop, on average, competes with an assemblage of 8 to 10 weed species (Bridges, 1992). CO_2 and climate can also affect weed demographics. For example, with field grown soybean, elevated CO_2 per se appeared to be a factor in increasing the relative proportion of C_3 to C_4 weedy species with subsequent reductions in soybean yields (Ziska and Goins, 2006). For rice and barnyard grass (C_4), increasing CO_2 favored rice, but if both temperature and CO_2 increased simultaneously, the C_4 weed was favored, primarily because higher temperatures resulted in increased seed yield loss for rice. For weeds that share physiological, morphological, or phenological traits with the crop, including those weeds that are wild relatives of the domesticated crop species (often among the "worst" weeds in agronomic situations, e.g., rice and red rice), the decrease in seed yield from weeds may be greater under elevated CO_2 (Ziska, 2010).

With respect to control, a number of studies have, to date, indicated a decline in herbicide efficacy in response to elevated CO_2 and/or temperature for some weed species, both C_3 and C_4 (Archambault, 2007; Manea et al., 2011). Some of the mechanisms for this are understood, for example, for the invasive plant species Canada thistle (*Cirsium arvense*), elevated CO_2 results in a greater root biomass, thus diluting the active ingredient of the herbicide used and reducing chemical control (Ziska, 2010). To date, studies on physical, cultural, or biological weed control are lacking.

7.3.2.4. Fisheries and Aquaculture

The natural and human processes in fisheries and aquaculture differ from mainstream agriculture and are particularly vulnerable to impacts and interactions related to climate change. Capture fisheries in particular, comprising the largest remaining example of harvesting natural, wild resources, are strongly influenced by global ecosystem processes. The social, economic, and nutritional requirements of the growing human population are already driving heavy exploitation of capture fisheries and rapid development of aquaculture (Section 6.4.1.1). This trend will continue over the next 20 to 30 years at least: Merino et al. (2012) forecast that in addition to a predicted small increase in marine fisheries production, between 71 and 117 million tonnes of fish will need to be produced by aquaculture to maintain current average per capita consumption of fish. The impacts of climate change add to and compound these threats to the sustainability of capture fisheries and aquaculture development (FAO, 2009a). Expected changes in the intensity, frequency, and seasonality of climate patterns and extreme events, sea level rise, glacier melting, ocean acidification, and changes in precipitation with associated changes in groundwater and river flows are expected to result in significant changes across a wide range of aquatic ecosystem types and regions with consequences for fisheries and aquaculture in many places (FAO, 2009a; see also Section 30.5.1.1). Ocean acidification will also have negative impacts on the culture of calcifying organisms (Section 30.6.2.1.4), including mollusc species of which 14.2 million tonnes were produced by aquaculture in 2010, equivalent to 23.6% of global aquaculture production (FAO, 2012). There are also concerns that climate change could lead to the spread of pathogens with impacts on wild and cultured aquatic resources (De Silva and Soto, 2009).

Given the proximity of fishing and aquaculture sites to oceans, seas, and riparian environments, extreme events can be expected to have impacts on fisheries and aquaculture with those located in low-lying

areas at particular risk. The consequences of sea level rise and the expected increased frequency and intensity of storms include increased risks of loss of homes and infrastructure, increased safety risks while fishing, and the loss of days at sea because of bad weather (Daw et al., 2009). In areas that experience water stress and competition for water resources, aquaculture operations and inland fisheries production will be at risk.

Food production from fisheries and aquaculture will be affected by the sensitivity of the caught and cultured species to climate change and both positive and negative outcomes can be expected. Changes in marine and freshwater mean temperatures, ocean acidification, hypoxia, and other climate-related changes will influence the distribution and productivity of fished and farmed aquatic species (Sections 6.4.3, 7.2.1.2, 30.6.2). Changes in temperature extremes are also likely to have impacts. Many aquatic species are routinely subjected to large daily and seasonal fluctuations in temperature and are able to cope with them: for example, temperatures in shallow coastal habitats in the tropical Pacific can vary by more than 14°C diurnally (Pratchett et al., 2011). Nevertheless, distribution and productivity of aquatic species and communities are sensitive to changes in temperature extremes. A study on salmon populations in Washington State, USA (Mantua et al., 2010), demonstrated important impacts of seasonal variations and extremes. The study concluded that warming in winter and spring would have some positive impacts while increased summertime stream temperatures, seasonal low flows, and changes in the peak and base flows would have negative impacts on the populations. Coral reefs are particularly susceptible to extremes in temperature: temperatures 1°C or 2°C in excess of normal maximums for 3 to 4 weeks are sufficient to disrupt the essential relationship between endosymbiotic dinoflagellates and their coral hosts, leading to coral bleaching. Large-scale bleaching of coral reefs has increased in recent decades both in intensity and frequency (Hoegh-Guldberg et al., 2007).

The impacts of climate change on the fisheries and aquaculture sector will have implications for the four dimensions of food security, that is, availability of aquatic foods, stability of supply, access to aquatic foods, and utilization of aquatic products (FAO, 2009a). Where climate-driven ecological changes are significant, countries and communities will need to adapt through, for example, changes in fishing and aquaculture practices and operations (Section 7.5.1.1.2).

7.3.2.5. Food and Fodder Quality and Human Health

Food quality is any characteristic other than yield that is valuable to the producer or consumer. Examples include wheat protein and starch concentrations, which affect dough quality; amylose content in rice, which affects taste; and mineral concentrations, which affects nutrient intake of consumers. Climate change will have some adverse impacts on food quality through both biotic and abiotic stresses (Ceccarelli et al., 2010). These changes may affect crop quality by altering carbon and nutrient uptake and biochemical processes that produce secondary compounds or redistribute and store compounds during grain development and maturation. This in turn could impact human and livestock health by altering nutritional intake and/or affect economic value by altering traits valuable to processers or the consumers.

Change in nitrogen concentration, a proxy for protein concentration, is the most examined quality trait and since AR4 studies have been extended to almost all the major food crops. Cereals grown in elevated CO_2 show a decrease in protein (Pikki et al., 2007; Högy et al., 2009; Erbs et al., 2010; Ainsworth and McGrath, 2010; DaMatta et al., 2010; Fernando et al., 2012). Meta-analysis of 228 experimental observations finds decreases between 10 and 14% in edible portions of wheat, rice, barley, and potato, but only 1.5% in soybeans, a nitrogen-fixing legume, when grown in elevated CO_2 (Taub et al., 2008).

Mineral concentration of edible plant tissues are affected by growth in elevated CO_2 in a similar manner to nitrogen. Although there are numerous studies measuring mineral concentration, there are relatively few measurements for any given mineral relevant to human health. Although there were several studies published before the release of AR4, this topic was not covered in any depth in AR4. Meta-analysis of studies prior to 2002 finds that phosphorus, calcium, sulfur, magnesium, iron, zinc, manganese, and copper decline by 2.5 to 20% in wheat grain and leaves of numerous species in elevated CO_2, but potassium increases insignificantly in wheat grain (Loladze, 2002; Högy et al., 2009; Fernando et al., 2012). Since 2002, studies generally find decreases in zinc, sulfur, phosphorus, magnesium, and iron in wheat and barley grain; increase in copper, molybdenum, and lead (from a limited number of studies); and mixed results for calcium and potassium (Högy et al., 2009; Erbs et al., 2010; Fernando et al., 2012). Changes in mineral concentration due to elevated CO_2 are determined by several factors including crop species, soil type, tissue (tubers, leaves, or grain) and water status.

Elevated CO_2 can lower the nutritional quality of flour produced from grain cereals (Högy et al., 2009; Erbs et al., 2010) and of cassava (Gleadow et al., 2009). When coupled with increased crop and pathogen biomass, elevated CO_2 can result in increased severity of the *Fusarium pseudograminearum* pathogen, leading to shriveled grains with low market value (Melloy et al., 2010).

Extreme temperatures and elevated CO_2 concentrations reduce milling quality of rice by increasing chalkiness, but can improve taste, through, for example, reduced amylase concentration (Yang et al., 2007). Cultivars vary in their susceptibility to these processes (Ambardekar et al., 2011; Lanning et al., 2011). Overall, there is *robust evidence* and *high agreement* that elevated CO_2 on its own likely results in decreased nitrogen concentrations. Combining knowledge of nitrogen and mineral studies, there is *medium evidence* and *medium agreement* that mineral concentrations will decline. The majority of these data are from wheat, with comparatively little information from key crops such as maize, rice, potato, and cassava; thus magnitudes are uncertain for these species.

Elevated O_3 concentrations appear to have the opposite effect as elevated CO_2. Meta-analysis of about 50 wheat experiments found that elevated O_3 increased grain protein concentration by decreasing yield (Pleijel and Uddling, 2012). For other species, studies find both increases and decreases of N and several minerals (Taub et al., 2008), and as such no firm conclusions can be drawn, but they mostly respond similarly. Likewise, experiments examining the effect of drought on mineral concentrations find both decreases and increases (Ghorbanian et al., 2011; Sun et al., 2011).

Confidence in the impact of climate, CO_2, and O_3 on food quality does not imply confidence in changes regarding human health for several reasons. Processing of food affects nutrient concentrations, when the nutrient-rich outer layers of rice are removed, leaving the starch dense endosperm. Also, elevated CO_2 can increase crop yield, thus increasing the overall yield of minerals (Duval et al., 2011) and permitting greater mineral consumption. Furthermore, since calorie intake is the primary concern in many food-insecure populations, even if intake of minerals is decreased, those negative effects could be outweighed by increased calorie intake. In assessing impacts on health, current diets must be considered. Decreased mineral intake will matter for those who currently do not meet, or just barely meet, requirements, but will not affect those who already exceed requirements. Little is known about combined effects of climate change factors on food quality or the economic and behavioral changes that will occur. Thus, there is little confidence regarding effects of climate change on human health through changes in nutrient composition.

7.3.2.6. Pastures and Livestock

Pastures response to climate change is complex because, in addition to the direct major atmospheric and climatic drivers (CO_2 concentration, temperature, and precipitation), there are important indirect interactions such as plant competition, perennial growth habits, seasonal productivity, and plant-animal interactions. Projected increases in temperature and the lengthening of the growing season should extend forage production into late fall and early spring, thereby decreasing the need for accumulation of forage reserves during the winter season in USA (Izaurralde et al., 2011). In addition, water availability may play a major role in the response of pasturelands to climate change although there are differences in species response (Izaurralde et al., 2011). There is general consensus that increases in CO_2 will benefit C_3 species; however, warmer temperatures and drier conditions will tend to favor C_4 species (Hatfield et al., 2011; Izaurralde et al., 2011; Chapter 4). While elevated atmospheric CO_2 concentrations reduce sensitivity to lower precipitation in grassland ecosystems and can reduce mortality and increase recovery during severe water stress events, it is still unclear how general this result is (Soussana et al., 2010).

Temperature is an important limiting factor for livestock. As productivity increases, be it increasing milk yield in dairy cattle or higher growth rates and leanness in pigs or poultry, so metabolic heat production increases and the capacity to tolerate elevated temperatures decreases (Zumbach et al., 2008; Dikmen and Hansen, 2009). Over the long term, single-trait selection for productivity will tend to result in animals with lower heat tolerance (Hoffmann, 2010). Recent work adds to previous understanding (WGII AR4 Chapter 5) and indicates that heat stress (*medium evidence*, *high agreement*) in dairy cows can be responsible for the increase in mortality and economic losses (Vitali et al., 2009); it affects a wide range of parameters in broilers (Feng et al., 2008a); it impairs embryonic development and reproductive efficiency in pigs (Barati et al., 2008); and affects ovarian follicle development and ovulation in horses (Mortensen et al., 2009). Water stress also limits livestock systems. Climate change will affect the water resources available for livestock via impacts on runoff and groundwater (Chapter 3). Populated river basins may experience changes in river discharge, and large human and livestock populations may experience water stress such that proactive or reactive management interventions will almost certainly be required (Palmer et al., 2008). Problems of water supply for increasing livestock populations will be exacerbated by climate change in many places in sub-Saharan Africa and South Asia.

7.3.3. Sensitivity of Food Security to Weather and Climate

7.3.3.1. Non-Production Food Security Elements

As indicated in the discussion in Section 7.1.1 and Figure 7-1, food security is dependent on access and consumption patterns, food utilization and nutrition, and overall stability of the system as much as food production and availability. The overall impact of climate change on food security is considerably more complex and potentially greater than projected impacts on agricultural productivity alone. Figure 7-1 indicates the main components of food security and their key elements. All of these will be affected by climate change to some extent. For example, climate change effects on water, sanitation, and energy availability have major implications for food access and utilization as well as availability. Likewise, changes in the frequency and severity of climate extremes can affect stability of food availability and prices, with consequent impacts on access to food.

7.3.3.2. Accessibility, Utilization, and Stability

7.3.3.2.1. Climate change impacts on access

As noted in the discussion in Section 7.1.3, change in the levels and volatility of food prices is a key determinant of food access. Given the hypothesis that climate change will be a contributing factor to food price increases, and hence its affordability, the vulnerability of households to reduced food access depends on their channel of food access (*medium evidence*, *medium agreement*). Table 7-1 divides households into five main categories of food access, indicating their relative impacts of food price increases.

Concern about the impact of increased food prices on poverty and food security arises due to the high share of income that poor consumers spend on food, thus generating a disproportionately negative effect of price increases on this group (FAO, 2011). A study by the World Bank estimated a net increase of 44 million people in extreme poverty in low- and middle-income countries as a result of food price increases since June 2010 (Ivanic et al., 2011).

The distribution of net food buyers and net food sellers varies considerably across countries and can be expected to change with the process of economic development (Zezza et al., 2008; Aksoy et al., 2010; FAO, 2011). Changing consumption patterns associated with dietary transitions that accompany income growth, urbanization, market development, and trade liberalization determine the rate and nature of food demand growth and nutritional levels, and thus is a key determinant of global and local food security (Kearney, 2010). However, the evidence base on potential climate change impacts on consumption patterns, or on other non-production elements of food security is thin, particularly when

Table 7-1 | Households divided into five categories of food access, indicating the impacts of food price increases.

Food access category	Characteristics	Impacts of food price increase on food access
Primarily subsistence (autarkic)	Subsistence farmers, herders, fishers, and forest-dependent populations; generally low share of population (Karfakis et al., 2011)	Limited impact
Food producers: net sellers	Generally lower share of population compared with net buyers (Aksoy and Sid-Dimelik, 2008; Zezza et al., 2008; FAO, 2011)	Positive impact through increased income effect. Major beneficiaries are those with greatest surplus (e.g., larger, more commercialized farms) (FAO, 2011)
Food producers: net buyers	Majority of poor rural households (IFAD, 2010; FAO, 2011)	Ambiguous: depends on relative size of income and price effects, but generally expected to be negative due to high share of income spent on food (Ivanic and Martin, 2008; FAO, 2011; Ivanic et al., 2011)
Rural non-farming households	Rural landless: characterized by high rates of food insecurity; average share of population for 15 low-income countries was 22% (Aksoy et al., 2010)	Negative impact due to high share of income spent on food; however, some limited evidence that wage increases may accompany price increases, in which case overall effects are ambiguous (Aksoy and Sid-Dikmelik, 2008; FAO, 2011)
Urban consumers	Growing share of population in most countries (IFAD, 2010)	Negative impact by reducing food affordability. Especially vulnerable to changes in global food prices, as they are more likely to consume staple foods derived from tradable commodities (FAO, 2008; Ivanic et al., 2011)

compared with the literature on climate change impacts on food production and availability.

Current and future variation in the distribution and vulnerability to loss of food access across household types makes impacts assessment complex and difficult. Nonetheless, there are reasons for concern about food access due to the current high rates of food insecurity in many low income countries. Agricultural producers who are net food buyers are particularly vulnerable. Similarly, low-income agricultural dependent economies that are net food importers, which are those that already have high rates of food insecurity, could experience significant losses in food access through a double negative effect on reduced domestic agricultural production and increased food prices on global markets.

7.3.3.2.2. Climate change impacts on stability

There is increasing evidence of and confidence in the effect of climate change on increasing the incidence and frequency of some types of climate extreme events (IPCC, 2012), and this will have significant impacts on food security (*medium evidence*, *medium agreement*). Recent experience of global climate patterns affecting food security indicates the potential nature and magnitude of increased variability. An impact assessment of the 2010 Pakistan floods surveyed 1800 households 6 months after the floods and found that 88% of the households reported income losses of up to 50%, with significantly higher rates in rural than urban areas (Kirsch et al., 2012). The same study indicated that loss of key services such as electricity, sanitation, and clean water resulted in lower standards of living even in the wake of significant relief attempts, again with significantly heavier effects on rural populations (Kirsch et al., 2012). The Russian heat wave of 2010 and subsequent export ban contributed to the more than doubling of global wheat prices by the end of the year. The degree to which these price increases affected domestic consumers and poverty depended on national responses in importing countries, although a significant net negative effect on poverty was found (Ivanic et al., 2011).

Increased incidence of climate extremes reduces incentives to invest in agricultural production, potentially offsetting positive impacts from increasing food price trends. This is particularly true for poor smallholders with limited or no access to credit and insurance. Greater exposure to climate risk, in the absence of well-functioning insurance markets, leads to (1) greater emphasis on low-return but low-risk subsistence crops (Roe and Graham-Tomasi, 1986; Fafchamps, 1992; Heltberg and Tarp, 2002), (2) a lower likelihood of applying purchased inputs such as fertilizer (Kassie et al., 2008; Dercon and Christiansen, 2011), (3) a lower likelihood of adopting new technologies (Feder et al., 1985; Antle and Crissman., 1990), and (4) lower investments (Skees et al., 1999). All of these responses generally lead to both lower current and future farm profits (*robust evidence*, *high agreement*) (Rosenzweig and Binswanger, 1993; Hurley, 2010).

It is also well documented that in many rural areas, smallholders in particular do not have the capacity to smooth consumption in the face of climate shocks, particularly generalized shocks that affect a majority of households in the same location (Dercon, 2004; Skoufias and Quisumbing, 2005; Dercon, 2006; Fafchamps, 2009; Prakash, 2011). Any increases in climate extremes will exacerbate the vulnerability of all food-insecure people, including smallholders (*robust evidence*, *high agreement*). Currently, smallholders rely to a large extent on increasing labor off-farm where possible (Fafchamps, 1999; Kazianga and Udry, 2006), but also by decreasing both food consumption and non-food expenditures, such as those on education and health care (*medium evidence*, *high agreement*; Skoufias and Quisumbing, 2005). Furthermore, some evidence also suggests that poorer households are more likely to reduce consumption, while wealthier households liquidate assets to cover current deficits (*limited evidence*, *medium agreement*; Kazianga and Udry, 2006; Carter and Lybbert, 2012). Reductions in food consumption, sales of productive assets, education, and health care can lead to long-term losses in terms of income generation and thus to future food security (*limited evidence*, *medium agreement*; Skoufias and Quisumbing, 2005; Hoddinot et al., 2008). Increased uncertainty of future climate conditions and increases in climate extremes will increase food insecurity unless these significant barriers to consumption and asset smoothing can be addressed (*medium evidence*, *medium agreement*).

7.3.3.2.3. Climate change impacts on utilization

Climate change impacts on utilization may come about through changes in consumption patterns in response to shocks, as well as changes in nutrient content of food as well as food safety (*medium evidence*, *medium agreement*). Rationing consumption to prioritize calorie-rich but nutrient-poor foods is another common response (Bloem et al.,

2010). The effects are a decrease in dietary quality as well as quantity, which are magnified by pre-existing vulnerabilities—and lead to long-term loss of health, productivity capacity, and low incomes (*medium evidence*, *medium agreement*) (Alderman, 2010; Bloem et al., 2010; Brinkman et al., 2010; Campbell et al., 2010; Sari et al., 2010). The biological effects of climate change on nutrient content of foods are one of the main pathways for effects on utilization. A summary of recent literature on the impacts of climate change on the composition of nutrients in food items is given in HLPE (2012). Research on grains generally shows lowering of protein content with elevated temperature and CO_2 levels (Erda et al., 2005; Ainsworth and McGrath, 2010; Hatfield et al., 2011). There is good agreement that for plant-derived foods, mycotoxins are considered the key issue for food safety under climate change (Miraglia et al., 2009). The impacts of climate change on mycotoxins in the longer term are complex and region-specific; temperatures may increase sufficiently to eliminate certain mycotoxin-producing species from parts of the tropics but, in colder tropical regions and temperate zones, infections may increase (Cotty and Jaime-Garcia, 2007).

7.3.4. Sensitivity of Land Use to Weather and Climate

As noted in the AR4, changes in land use, for example, adjusting the location of crop production, are a potential adaptation response to climate change. Studies since the AR4 have confirmed that high-latitude locations will, in general, become more suitable for crops (Iqbal et al., 2009). Trnka et al. (2011), for example, examined projections of eleven agro-climatic indices across Europe, and found that declines in frost occurrence will lead to longer growing seasons, although temperature and moisture stress will often lead to greater interannual variability in crop suitability. The potential influence of pests and diseases is commonly beyond the scope of such studies (Gregory et al., 2009).

For tropical systems where moisture availability or extreme heat rather than frost limits the length of the growing season, there is a likelihood that the length of the growing season and overall suitability for crops will decline (*medium evidence*, *medium agreement*; Jones and Thornton, 2009; Zhang and Cai, 2011). For example, half of the wheat-growing area of the Indo-Gangetic Plains could become significantly heat stressed by the 2050s, while temperate wheat environments will expand northwards as climate changes (Ortiz et al., 2008). Similarly, by 2050, the majority of African countries will experience climates over at least half of their current crop area that lie outside the range currently experienced within the country (Burke et al., 2009). The majority of these novel climates have analogs in other African countries. In mountainous regions, where temperature varies significantly across topography, changes in crop suitability can be inferred from the variation of temperature across topography. The resulting vertical zones of increasing, decreasing, and unchanging suitability can be relatively robust in the face of uncertainty in future climate (Schroth et al., 2009).

The interaction between water resources and agriculture is expected to become increasingly important as climate changes. For example, whilst projected changes in crop productivity in China are uncertain, even within a single emissions scenario, irrigation has significant adaptation potential (Piao et al., 2010). However, limitations to availability of water will affect this potential. Changes in water use, including increased water diversion and development to meet increasing water demand,

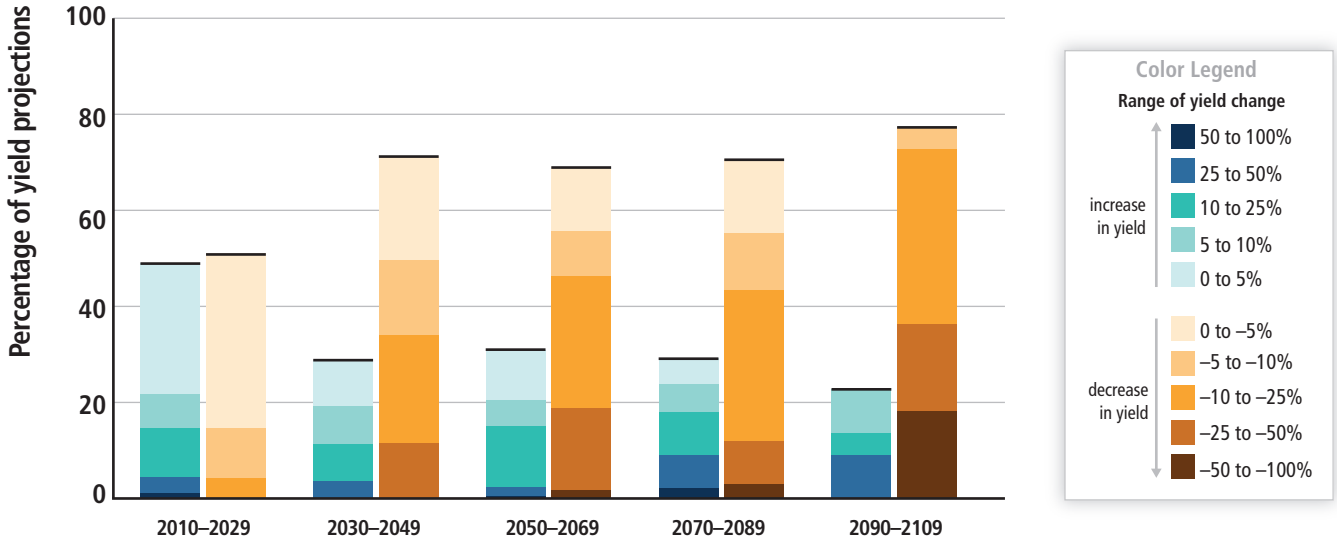

Figure 7-5 | Summary of projected changes in crop yields, due to climate change over the 21st century. The figure includes projections for different emission scenarios, for tropical and temperate regions, and for adaptation and no-adaptation cases combined. Relatively few studies have considered impacts on cropping systems for scenarios where global mean temperatures increase by 4°C or more. For five timeframes in the near-term and long-term, data (n=1090) are plotted in the 20-year period on the horizontal axis that includes the midpoint of each future projection period. Changes in crop yields are relative to late-20th-century levels. Data for each timeframe sum to 100%. Projections taken from Abraha and Savage, 2006; Alexandrov and Hoogenboom, 2000; Arndt et al., 2011; Berg et al., 2013; Brassard and Singh, 2008; Brassard and Singh, 2007; Butt et al., 2005; Calzadilla et al., 2009; Chhetri et al., 2010; Ciscar et al., 2011; Deryng et al., 2011; Giannakopoulos et al., 2009; Hermans et al., 2010; Iqbal et al., 2011; Izaurralde et al, 2005; Kim et al., 2010; Lal, 2011; Li et al., 2011; Lobell et al., 2008; Moriondo et al., 2010; Müller et al., 2010; Osborne et al., 2013; Peltonen-Sainio et al., 2011; Piao et al., 2010; Ringler et al., 2010; Rowhanji et al., 2011; Schlenker and Roberts, 2009; Shuang-He et al., 2011; Southworth et al., 2000; Tan et al., 2010; Tao & Zhang, 2010; Tao and Zhang, 2011; Tao et al., 2009; Thornton et al., 2009; Thornton et al., 2010; Thornton et al., 2011; Tingem and Rivington, 2009; Tingem et al., 2008; Walker and Schulze, 2008; Wang et al., 2011; Xiong et al., 2007; Xiong et al., 2009.

and increased dam building will also have implications for inland fisheries and aquaculture, and therefore for the people dependent on them (Ficke et al., 2007; FAO, 2009a). In the case of the Mekong River basin, a large proportion of the 60 million inhabitants are dependent in some way on fisheries and aquaculture that will be seriously impacted by human population growth, flood mitigation, increased offtake of water, changes in land use, and overfishing, as well as by climate change (Brander, 2007). Ficke et al. (2007) reported that at that time there were 46 large dams planned or already under construction in the Yangtze River basin, the completion of which would have detrimental effects on those dependent on fish for subsistence and recreation.

The models used in projections of land suitability and cropland expansion discussed above rely on assumptions about non-climatic constraints on crop productivity, such as soil quality and access to markets. These assumptions are increasingly amenable to testing as the climate system shifts, by comparing observed changes in cropland area with model predictions. The location of the margin between cropping land and extensive grazing in southern Australia has varied with decadal climate conditions and is projected to shift toward the coast with hotter and drier conditions, notwithstanding the positive impacts of elevated CO_2 (Nidumolu et al., 2012). Recent trends in climate have seen reductions in cropping activity consistent with these projections (Nidumolu et al., 2012).

7.4. Projected Integrated Climate Change Impacts

7.4.1. Projected Impacts on Cropping Systems

Crop yields remain the most well studied aspect of food security impacts from climate change, with many projections published since AR4. These newer studies confirm many of the patterns identified in AR4, such as negative yield impacts for all crops past 3°C of local warming without adaptation, even with benefits of higher CO_2 and rainfall (Figure 7-4).

Figure 7-5 shows projected impacts on mean crop yield in 20-year bins, including cases with no adaptation and a range of incremental adaptations. The data indicate that negative impacts on average yields become *likely* from the 2030s. Negative impacts of more than 5% are *more likely than not* beyond 2050 and *likely* by the end of the century. Some important differences by emission scenario and region are masked in Figure 7-5. From the 2080s onwards, negative yield impacts in the tropics are *very likely*, regardless of adaptation or emission scenario. This is consistent with the meta-analysis of Knox et al. (2012), and a recent model intercomparison of global gridded crop models (Rosenzweig et al., 2013, 2014).

A few studies have explicitly compared projections for different regions or crops to identify areas at most risk. Lobell et al. (2008) used a statistical crop model with 20 GCMs and identified South Asia and southern Africa as two regions that, in the absence of adaptation, would suffer the most negative impacts on several important crops. Yields changes have also been assessed by regional meta-analyses: Knox et al. (2012) synthesized projections from 52 studies and estimated an expected 8% negative yield impact in both regions by 2050 averaged over crops, with wheat, maize, sorghum, and millets more affected than rice, cassava, and sugarcane.

Changes in the interannual variability of yields could potentially affect stability of food availability and access. Figure 7-6 shows projected changes in the coefficient of variation (CV) of yield from some of the few studies that publish this information. The data shown are consistent with reports of CV elsewhere: Müller et al. (2014) conducted gridded simulations across the globe and reported an increase of more than 5% in CV in 64% of grid cells, and a decrease of more than 5% in 29% of cases. Increases in CV can be due to reductions in mean yields and/or increases in standard deviation of yields, and often simulated changes are a combination of the two. Overall, climate change will increase crop yield variability in many regions (*medium evidence*, *medium agreement*).

Estimated impacts of both historical and future climate changes on mean yields are summarized along with projected impacts on yield variability in Figure 7-7, with all impacts expressed as the average percentage impact per decade. This comparison illustrates that future impacts are expected to be consistent with the trajectory of past impacts, with the majority of locations experiencing negative impacts while some locations benefit. Each additional decade of climate change is expected to reduce mean yields by roughly 1%, which is a small but nontrivial fraction of the anticipated roughly 14% increase in productivity per decade needed to keep pace with demand. For future projections, enough studies are available to assess differences by region and adaptation scenario, with significant adaptation effects apparent mainly in temperate systems (Section 7.5).

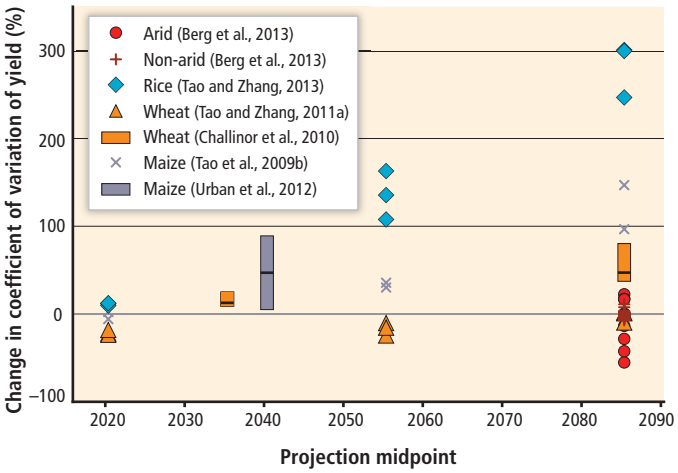

Figure 7-6 | Projected percentage change in coefficient of variation (CV) of yield for wheat (Tao and Zhang, 2011a; Challinor et al., 2010), maize (Tao et al., 2009b; Urban et al., 2012), rice (Tao and Zhang, 2013), and C_4 crops (arid and non-arid, Berg et al., 2013). The data from Urban et al. (2012) show the range (mean plus and minus one standard deviation) of percentage changes in CV. For the Challinor et al. (2010) data, paired CV changes were not available, so the box shows changes in the mean CV, the mean CV plus one standard deviation, and the mean CV minus one standard deviation. All other studies plot individual data points. A total of 81 data points are plotted in the figure, although the underlying data consist of many thousands of crop model simulations. The studies used a range of scenarios (Special Report on Emissions Scenarios (SRES) A1B, A2, A1FI, and B1). Berg et al. (2013) is a global study of the tropics, Urban et al. (2012) is for US maize, and the remaining data points are for China.

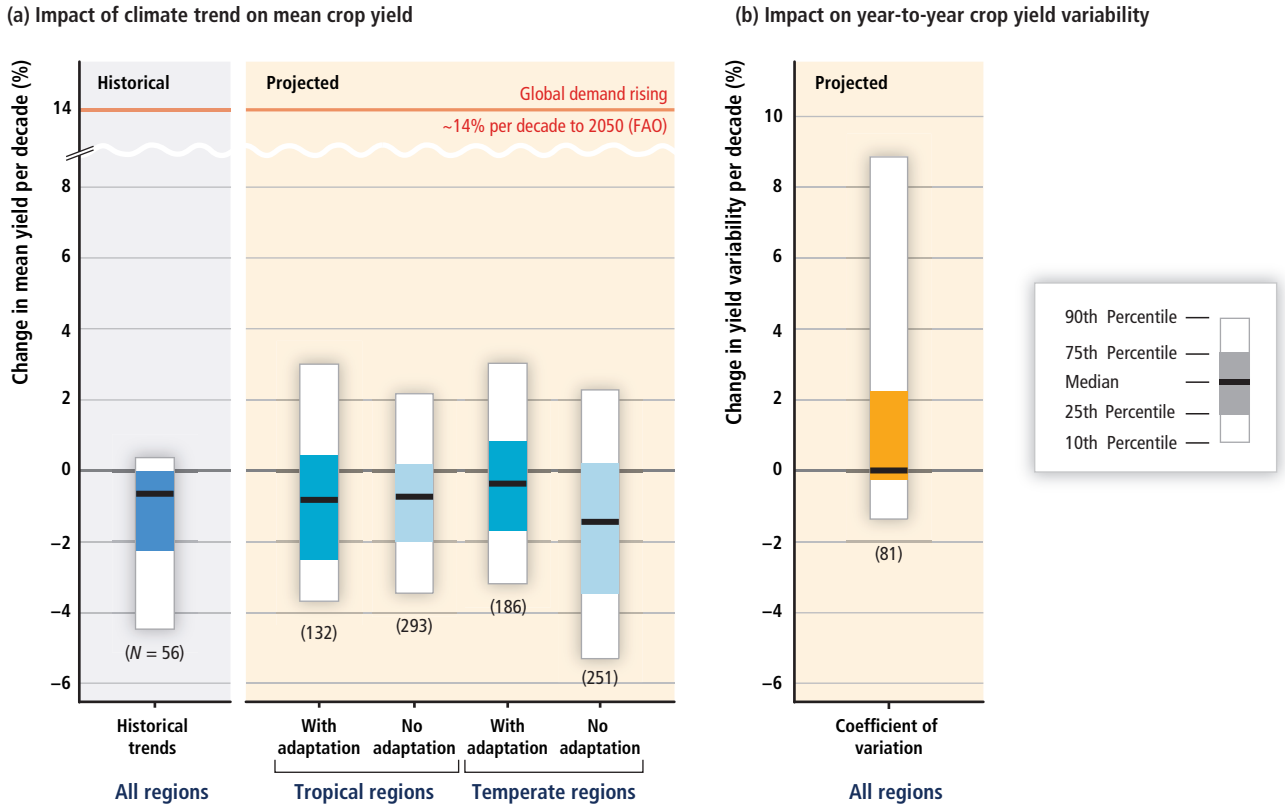

Figure 7-7 | Boxplot summary of studies that quantify impact of climate and CO_2 changes on crop yields, including historical and projected impacts, mean and variability of yields, and for all available crops in temperate and tropical regions. All impacts are expressed as average impact per decade (a 10% total impact from a 50-year period of climate change would be represented as 2% per decade). References for historical impacts are given in Figure 7-2, for projected mean yields in Figure 7-5, and for yield variability in Figure 7-6. *N* indicates the number of estimates, with some studies providing multiple estimates. In general, decreases in mean yields and increases in yield variability are considered negative outcomes for food security. Also indicated in the figure is the expected increase in crop demand of 14% per decade (Alexandratos and Bruinsma, 2012), which represents a target for productivity improvements to keep pace with demand.

Relatively few studies have considered impacts on cropping systems for scenarios where global mean temperatures increase by 4°C or more. An analysis for sub-Saharan Africa predicted overall decreases of 19% for maize yields, 68% decrease for bean yields, and a small increase for fodder grass (*Brachiaria decumbens*) given 5°C global average warming (Thornton et al., 2011). Rötter et al. (2011) conclude that positive effects of modest warming and increased CO_2 levels on crop yields in Finland will be reversed at global temperatures increases of 4°C, leading to negative yield impacts in excess of 20% in relation to current conditions.

For perennial crops, winter chill accumulation that is important to many fruit and nut trees is projected to continue its decline, with, for instance, a 40 chill-hours per decade reduction projected for California for the period up to 2100 (Baldocchi and Wong, 2008). Averaging over three GCMs, annual winter chill loss by 2050 compared to 1970 would amount 17.7% to 22.6% in Egypt (Farag et al., 2010). Several studies have projected negative yield impacts of climate trends for perennial trees, including apples in eastern Washington (Stöckle et al., 2010) and cherries in California (Lobell and Field, 2011), although CO_2 increases may offset some or all of these losses. Reductions in suitability for grapevine are expected in most of the wine-producing regions (Hall and Jones, 2009; White et al., 2009; Jones et al., 2010). Wine grape production and quality will be affected in Europe, USA, Australia (Jones et al., 2005; Wolfe et al., 2008; Cozzolino et al., 2010; Chapter 25), although it could be a benefit in Portugal (Santos et al., 2011) and British Columbia in Canada (Rayne et al., 2009). Important crops in Brazil such as sugarcane and coffee are expected to migrate toward more favorable zones in the South (Pinto, 2007; Pinto et al., 2008; Chapter 27). Sugarcane fresh stalk mass is generally expected to gain from both warming and elevated CO_2 in Brazil (Marin et al., 2013). The suitability for coffee crops in Costa Rica, Nicaragua, and El Salvador will be reduced by more than 40% (Glenn et al., 2013) while the loss of climatic niches in Colombia will force the migration of coffee crops toward higher altitudes by mid-century (Ramirez-Villegas et al., 2012). In the same way, increases in temperature will affect tea production, in particular at low altitudes (Wijeratne et al., 2007).

Consideration of pest, weed, and disease impacts are omitted from most yield projections, yet other studies have focused on projecting impacts of these biotic stressors. For pests and diseases, range expansion has been predicted for the destructive *Phytophthora cinnamomi* in Europe (Bergot et al., 2004) and for phoma stem canker on oilseed rape in the UK (Evans et al., 2008). Increased generations under climate change for the coffee nematode have been predicted for Brazil (Ghini et al., 2008). Walnut pests in California are predicted to experience increased numbers of generations under climate change scenarios (Luedeling et al., 2011). Luck et al. (2011) summarized the mixed results for the qualitative effects of climate change on pathogens that cause disease of four major food crops—wheat, rice, soybean, and potato—where some diseases increased in risk while others decreased under climate change scenarios. In syntheses, there is a tendency for risk of insect

damage to plants to increase (Paulson et al., 2009). Typical scenario analyses are limited by simplistic assumptions, and work remains to evaluate how conclusions will change as more complete scenarios, such as those including migration and invasion patterns and other types of global change, are considered (Savary et al., 2005; Garrett et al., 2011). Effects on soil communities represent an area that needs more attention (Pritchard, 2011). Mycotoxins and pesticide residues in food are an important concern for food safety in many parts of the world, and identified as an important issue for climate change effects in Europe (Miraglia et al., 2009).

Weed populations and demographics are expected to change (*medium confidence*), with an overall poleward migration in response to warming (Ziska et al., 2011). An overview of crop and weed competitive studies indicate that weeds could limit crop yields to a greater extent with rising levels of CO_2 per se (Ziska, 2010). This may be related to the greater degree of phenotypic and genotypic plasticity associated with weedy species relative to the uniformity inherent in large cropping systems (Section 4.2.4.6). Chemical control of weeds, which is the preferred management method for large-scale farms, may become less effective (*limited evidence*, *medium agreement*), with increasing economic and environmental costs (Section 7.3.2.3).

Climate change effects on productivity will alter land use patterns, both in terms of total area sown to crops and the geographic distribution of that area. For example, the suitability for potato crops is expected to increase in very high latitudes and high tropical altitudes toward 2100 (Schaefleitner et al., 2011). Given expected trends in population, incomes, bioenergy demand, and agricultural technology, global arable area is projected to increase from 2007 to 2050, with projected increases over this period of +9% (Bruinsma, 2009), +8% (Fischer et al., 2009), +10 to 20% (Smith et al., 2010), and +18 to 23% (Lobell et al., 2013b) (*medium evidence*, *medium agreement*). Not all such studies included the effects of global warming. Where this is the case, estimates range from a 20% increase in cropping area to a decline of 9% (Zhang and Cai, 2011), but with large regional differences (*limited evidence*, *low agreement*). Countries at northern latitudes and under the current constraint of low temperature may increase cultivated area (*limited evidence*, *low agreement*). The generally lower nutrient quality of soils and the lack of necessary infrastructure required to convert virgin land into productive arable land make estimates of cropping area increases highly uncertain.

7.4.2. Projected Impacts on Fisheries and Aquaculture

Many studies have projected impacts of climate change on capture fisheries (Chapters 6 and 30) and only a subset of the more indicative studies at different ecological and geographical scales is included here. Overall, there is *high confidence* that climate change will impact on fisheries production with significant negative impacts particularly for developing countries in tropical areas, while more northerly, developed countries may experience benefits (Section 6.4.3).

Simulation studies on skipjack and bigeye tuna in the Pacific under both the Special Report on Emissions Scenarios (SRES) B1 and A2 scenarios indicate that catches of skipjack in the region as a whole are likely to increase by approximately 19% in 2035 compared to recent catch levels while catches of bigeye are projected to increase only marginally. By 2100, under the B1 scenario, catches of skipjack are projected to be 12.4% higher than recent levels but 7.5% lower under the A2 scenario, while catches of bigeye will be 8.8% and 26.7% lower under the B1 and A2 scenarios, respectively. The models indicate important regional differences, with a general trend that catches of tuna will decrease in the Western Pacific and increase in the Eastern Pacific (Lehodey et al., 2011; see also Sections 6.5.3, 30.6.2.1.1). These changes have important implications for the future of national fishing fleets and canneries in the Western Pacific (Bell et al., 2009). Climate change is expected to impact directly on the productivity of coastal fisheries in the Pacific island countries and territories through increased sea surface temperature and ocean acidification and indirectly through climate-driven damage to coral reefs, mangroves, seagrasses, and intertidal flats (Pratchett et al., 2011). Extreme events such as increased severity of tropical cyclones could also impact on some species. Under both B1 and A2 emissions scenarios, the vulnerability of coastal fisheries as a whole in 2035, as estimated through the framework described in Bell et al. (2009), is considered to be low. Extended to 2100, the projected impacts under the A2 emissions scenario are more severe, with reductions in coastal fisheries production by 20 to 35% in the west and 10 to 30% in the east (Pratchett et al., 2011).

Frequently Asked Questions

FAQ 7.2 | How could climate change interact with change in fish stocks and ocean acidification?

Millions of people rely on fish and aquatic invertebrates for their food security and as an important source of protein and some micronutrients. However, climate change will affect fish stocks and other aquatic species. For example, increasing temperatures will lead to increased production of important fishery resources in some areas but decreased production in others while increases in acidification will have negative impacts on important invertebrate species, including species responsible for building coral reefs that provide essential habitat for many fished species in these areas. The poorest fishers and others dependent on fisheries and subsistence aquaculture will be the most vulnerable to these changes, including those in Small Island Developing States, central and western African countries, Peru and Colombia in South America, and some tropical Asian countries.

Brown et al. (2010) project that, under the A2 emissions scenario, primary production in the ocean around Australia will increase over the 50-year period from 2000 to 2050 as a result of small increases in nutrient availability from changes in ocean stratification and temperature, although the authors acknowledge considerable model uncertainty. This increase is forecast, in general, to benefit fisheries catch and value. In a complementary study, Fulton (2011) used available end-to-end models to forecast the impacts of climate change under the A2 scenario across approximately two-thirds of Australia's exclusive economic zone. The results indicated that by 2060, the large-scale commercial fisheries, aided by their adaptive flexibility, would experience an overall increase of more than 90% in the value of their operations, although differing across sectors. The change in returns for the small-scale sector varied regionally from a decrease of 30 to 51% to a potential increase of 9 to 14%.

At the global scale, projections based on a dynamic bioclimatological envelope model under the SRES A1B scenario suggested that climate change could lead to an average 30 to 70% increase in fisheries yield from high-latitude regions (>50°N in the Northern Hemisphere), but a decrease of up to 40% in the tropics by 2055 compared to yields obtained in 2005 (Cheung et al., 2010). Another study using a suite of models linking physical, ecological, fisheries, and bioeconomic processes projected that, under the A1B scenario, the global yield from "large" fish could increase by 6% and that of the "small fish" used in fishmeal production by approximately 3.6%, assuming that marine fisheries and fish resources would be managed sustainably (Merino et al., 2012).

There is limited information available on projected impacts on food production in inland fisheries. Xenopoulus et al. (2005) investigated the effect of climate change and water withdrawal on freshwater fish extinctions under the assumptions of two scenarios consistent with scenarios A2 and B2. They forecast that discharge would increase in between 65 and 70% of river basins in the world but it would decrease by as much as 80% in 133 rivers for which fish species data were available. In the latter group, by 2070, up to 75% (quartile range, 4-22%) of the local fish biodiversity would be "headed toward extinction" because of changes in climate and water consumption, with the highest rates of extinction forecast mainly in tropical and subtropical areas. These results are not directly translatable into changes in fishery production but do give cause for concern for the likely affected areas (*limited evidence*, *low agreement*).

Information on future impacts on aquaculture is equally limited. Huppert et al. (2009) considered the impacts on the coast of Washington State, USA. They concluded that inundation of low-lying coastal areas from sea level rise, flooding from major storm events, and increased ocean temperatures and acidification would create significant challenges for the important shellfish aquaculture industry in the state. Inundation of existing shellfish habitats from sea level rise and increased incidence of harmful algal blooms were also contributory factors. Using a structured vulnerability framework and considering the B1 and A2 emission scenarios to project impacts on aquaculture in the tropical Pacific to 2035 and 2100, Pickering et al. (2011) concluded that production of freshwater species such as tilapia, carp, and milkfish will probably benefit from the expected climate changes, while coastal enterprises are expected to encounter problems in the same time horizons, varying according to species. Aquaculture production of calcifying organisms such as molluscs will experience loss of suitable habitats through ocean acidification. This will be particularly pronounced at and in the vicinity of eastern boundary upwelling systems (Section 30.6.2.1.4).

The food security consequences of the different impacts on capture fisheries and aquaculture are more difficult to estimate than the biological and ecological consequences. A preliminary study by Allison et al. (2009) examined the vulnerability of the economies of 132 countries to climate change impacts on fisheries in 2050 under the A1FI and B2 scenarios. Vulnerability was considered as a composite of three components: exposure to the physical effects of climate change, the sensitivity of the country to impacts on fisheries, and adaptive capacity within the country. This analysis suggested that under both scenarios several of the least developed countries were also among the most vulnerable to climate change impacts on their fisheries. They included countries in central and western Africa, Peru and Colombia in South America, and four tropical Asian countries.

7.4.3. Projected Impacts on Livestock

Climate change impacts on livestock will include effects on forage and feed, direct impacts of changes in temperature and water availability on animals, and indirect effects via livestock diseases. Many of the relevant processes and projected impacts for rangelands are discussed in Section 4.3.3.2, as well as in chapters for regions with prominent livestock sectors (Sections 22.3.4.2, 23.4.2, 25.7.2.1). In North American cattle systems, warming is expected to lengthen forage growing season but decrease forage quality, with important variations due to rainfall changes (Craine et al., 2010; Hatfield et al., 2011; Izaurralde et al., 2011). Simulations for French grasslands (Graux et al., 2013) and sown pastures in Tasmania (Perring et al., 2010) also project negative impacts on forage quality. Similarly, legume content of grasslands in most of southern Australia is projected to increase to the 2070s for SRES A2, with larger increases in wetter locations (Moore and Ghahramani, 2013).

There is *high confidence* that high temperatures tend to reduce animal feeding and growth rates (André et al., 2011; Renaudeau et al., 2011). The impacts of a changing UK climate on dairy cow production were analyzed by Wall et al. (2010), who showed that, in some regions, milk yields will be reduced and mortality increased because of heat stress throughout the current century, with annual production and mortality losses amounting to some £40 million by the 2080s under a medium-high GHG emission scenario.

Existing challenges of supplying water for an increasing livestock population will be exacerbated by climate change in many places (*limited evidence*, *high agreement*). For example, Masike and Urich (2008) project that warming under SRES A1 emission scenario will cause an annual increase of more than 20% in cattle water demand by 2050 for Kgatleng District, Botswana. At the same time, there is ample scope to improve livestock water productivity considerably (Molden et al., 2010); for example, in mixed crop-livestock systems of sub-Saharan Africa via feed, water, and animal management (Descheemaeker et al., 2010).

Host and pathogen systems in livestock will change their ranges because of climate change (*high confidence*). Species diversity of some

Box 7-1 | Projected Impacts for Crops and Livestock in Global Regions and Sub-Regions under Future Scenarios

Projected impacts for crops and livestock in global regions and sub-regions under future scenarios. Crop yield impacts in parentheses correspond to parentheticals in the scenario column. $-CO_2$ = without CO_2 effects; $+CO_2$ = with CO_2 effects; (I) = irrigated; (R) = rainfed. ARPEGE = Action de Recherche Petite Echelle Grande Echelle; CSIRO = Commonwealth Scientific and Industrial Research Organisation; ECHAM4 = European Centre for Medium Range Weather Forecasts Hamburg 4; GFDL-CM2.0/2 = Geophysical Fluid Dynamics Laboratory-Climate Model 2.0/2; HadCM3 = Met Office Hadley Centre Climate Prediction Model 3; HIRHAM = High-Resolution Hamburg Climate Model; MIROC = Model for Interdisciplinary Research On Climate; MPI-OM = Max Planck Institute; MRI-CGCM2.3.2 = Meteorological Research Institute of Japan Meteorological Agency-Coupled General Circulation Model 2.3.2; PRECIS = Providing Regional Climates for Impact Studies; RCA3 = Rossby Centre Regional Atmospheric Model 3.

Regional impacts on crops

Region	Sub-region	Yield impacts (%)	Scenario	Reference
World		• (I) Maize: –4, –7 • (R) Maize: –2, –12 • (I) Rice: –9.5, –12 • (R) Rice: –1, +0.07 • (I) Wheat: –10, –13 • (R) Wheat: –4, –10	A1B CSIRO, MIROC 2050	Nelson et al. (2010)
East Asia	China	(I) Maize: • –10.9 to –1.4 (–7.8 to –1.6), • –21.7 to –9.8 (–16.4 to –10.2), • –32.1 to –4.3 (–26.6 to –3.9) (R) Maize: • –22.2 to –1.0 (–10.8 to +0.7), • –27.6 to –7.9 (–18.1 to –5.6), • –33.7 to –4.6 (–25.9 to –1.6) (I) Rice: • –18.6 to –6.1 (–10.1 to +3.3), • –31.9 to –13.5 (–16.1 to +2.5), • –40.2 to –23.6 (–19.3 to +0.18)	+1°C, +2°C, +3°C $-CO_2$ ($+CO_2$)	Tao et al. (2011)
	Eastern China	Rice: • –10 to +3 (+7.5 to +17.5), • –26.7 to +2 (0 to +25), • –39 to –6 (–10 to + 25)	2030, 2050, 2080 $-CO_2$ ($+CO_2$)	Tao and Zhang (2013)
	Huang-Huai-Hai Plain, China	Wheat–maize: +4.5 ± 14.8, –5.8 ± 25.8	+2°C, +5°C	Liu et al. (2010)
	North China Plain	• (I) Wheat: –0.9 (+23) • (R) Wheat: –1.9 (+28)	A1B 2085–2100 $-CO_2$ ($+CO_2$) MIROC	Yang et al. (2013)
	Yangtze River, China	• (I) Rice: –14.8 (–3.3) • (R) Rice: –15.2 (–4.1)	B2 2021–2050 $-CO_2$ ($+CO_2$)	Shen et al. (2011)
South Asia	South Asia	• Maize: –16 • Sorghum: –11	2050	Knox et al. (2012)
	South Asia	Net cereal production –4 to –10	+3°C	Lal (2011)
	India	Winter sorghum: up to –7, –11, –32	A2 2020, 2050, 2080	Srivastava et al. (2010)
		• (I) Rice: –4, –7, –10 • (R) Rice: –6, –2.5, –2.5	A1B; A2; B1; B2 2020, 2050, 2080 $+CO_2$ MIROC; PRECIS/HadCM3	Kumar et al. (2013)
		• Monsoon maize: –21 to 0, –35 to 0, –35 to 0 • Winter maize: –13 to +5, –50 to +5, –60 to –21	A2 2020, 2050, 2080 HadCM3	Byjesh et al. (2010)
	Northeast India	• (I) Rice: –10 to +5 • (R) Rice: –35 to +5 • Maize: up to –40 • Wheat: up to –20	A1B 2030 $+CO_2$ PRECIS/HadCM3	Kumar et al. (2011)
	Coastal India	• (I) Rice: –10 to +5 • (R) Rice: –20 to +15 • (I) Maize: –50 to –15 • (R) Maize: –35 to +10		
	Western Ghats, India	• (I) Rice: –11 to +5 • (R) Rice: –35 to +35 • Maize: up to –50 • Sorghum: up to –50		
	Pakistan	Wheat: –7, –24 (Swat); +14, +23 (Chitral)	+1.5°C, +3°C	Section 24.4.4.3
		• Wheat: –6, –8 • Rice: –16, –19	B2, A2 2080	Iqbal et al. (2009)

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Box 7-1 (continued)

Region	Sub-region	Yield impacts (%)	Scenario	Reference
West Asia	Yarmouk Basin, Jordan	• Barley: –8, +5 • Wheat: –20, +18	–20%, +20% precipitation	Al-Bakri et al. (2010)
Africa	All regions	• Wheat: –17 • Maize: –5 • Sorghum: –15 • Millet: –10	2050	Knox et al. (2012)
	All regions	Maize: –24 ± 19	2090 +5°C	Thornton et al. (2011)
	East Africa	• Maize: –3.1 to +15.0, –8.6 to +17.8 • Beans: –1.5 to +21.8, –18.1 to +23.7	A1FI; B1 2030, 2050 HadCM3; ECHam4	Thornton et al. (2010)
	Sahel	Millet: –20, –40	+2°C, +3°C	Ben Mohamed (2011)
Central & South America	Northeastern Brazil	• Maize: 0 to –10 • Wheat: –1 to –14 • Rice: –1 to –10	2030	Table 27-5; Lobell et al. (2008)
	Southern Brazil	• Maize: –15 • Bean: up to +45	A2 2080 +CO_2 HadCM3	Table 27-5; Costa et al. (2009)
	Paraguay	• Wheat: +4, –9, –13 (–1, +1, –5) • Maize: +3, +3, +8 (+3, +1, +6) • Soybean: 0, –10, –15 (0, –15, –2)	A2 (B2) 2020, 2050, 2080 PRECIS	Table 27-5; ECLAC (2010)
	Central America	• Wheat: –1 to –9 • Rice: 0 to –10	2030	Table 27-5; Lobell et al. (2008)
		• Maize: 0, 0, –10, –30 • Bean: –4, –19, –29, –87 • Rice: +3, –3, –14, –63	A2 2030, 2050, 2070, 2100	Table 27-5; ECLAC (2010)
	Panama	Maize: –0.5, +2.4, +4.5 (–0.1, –0.8, +1.5)	A2 (B1) 2020, 2050, 2080 +CO_2	Table 27-5; Ruane et al. (2013)
	Andean region	• Wheat: –14 to +2 • Barley: 0 to –13 • Potato: 0 to –5 • Maize: 0 to –5	2030	Table 27-5; Lobell et al. (2008)
	Chile	• Maize: –5% to –10% • Wheat: –10% to –20%	A1FI 2050 +CO_2 HadCM3	Table 27-5; Meza and Silva (2009)
	Argentina	• Wheat: –16, –11 (+3, +3) • Maize: –24, –15 (+1, 0) • Soybean: –25, –14 (+14, +19)	A2, B2 2080 –CO_2 (+CO_2) PRECIS	Table 27-5; ECLAC (2010)
North America	Midwestern United States	• Maize: –2.5 (–1.5) • Soy: +1.7 (+9.1)	+0.8°C –CO_2 (+CO_2)	Hatfield et al. (2011)
	Southeastern United States	• Maize: –2.5 (–1.5) • Soy: –2.4 (+5.0)		
	United States Great Plains	Wheat: –4.4 (+2.4)		
	Northwestern United States	• Winter wheat: +19.5, +29.5 • Spring wheat: –2.2, –5.6	A1B 2040, 2080 +CO_2	Stöckle et al. (2010)
	Canadian prairies	• Small grains: –48 to +18 • Oilseeds: –50 to +25	+1°C, +2°C, +20% precipiation, –20% precipitation	Kulshreshtha (2011)
Europe	Boreal	Wheat, maize, soybean: +34 to +54	A2, B2 2080 HadCM3/HIRHAM, ECHAM4/RCA3	Iglesias et al. (2012)
	Alpine	Wheat, maize, soybean: +20 to +23		
	Atlantic North	Wheat, maize, soybean: –5 to +22		
	Atlantic Central	Wheat, maize, soybean: +5 to +19		
	Atlantic South	Wheat, maize, soybean: –26 to –7		
	Continental North	Wheat, maize, soybean: –8 to +4		
	Continental South	Wheat, maize, soybean: +11 to +33		
	Mediterranean North	Wheat, maize, soybean: –22 to 0		
	Mediterranean South	Wheat, maize, soybean: –27 to +5		

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Box 7-1 (continued)

Region	Sub-region	Yield impacts (%)	Scenario	Reference
Australia	South	Wheat: –15, –12	A2; Low, high plant available water capacity 2080 +CO_2 CCAM	Luo et al. (2009)
	Southeast	Wheat: –29 (–25)	B2, A2, A1FI 2080 –CO_2 (+CO_2) CCAM	Anwar et al. (2007)

Regional impacts on livestock

Region	Sub-region	Climate change impacts	Scenarios	Reference
Africa	Botswana	Cost of supplying water from boreholes could increase by 23% due to increased hours of pumping, under drier and warmer conditions.	A2, B2 2050	Section 22.3.4.2
	Lowlands of Africa	Reduced stocking of dairy cows, a shift from cattle to sheep and goats, due to high temperature.		
	Highlands of East Africa	Livestock keeping could benefit from increased temperature.		
	East Africa	Maize stover availability per head of cattle may decrease due to water scarcity.		
	South Africa	Dairy yields decrease by 10–25%.	A2 2046–2065/2080–2100 ECHAM5/MPI-OM, GFDL-CM2.0/2, MRI-CGCM2.3.2	Nesamvuni et al. (2012)
Europe	Netherlands	Dairy production affected at daily mean temperatures above 18°C		Section 23.4.2
	Italy	Mortality risk to dairy cattle increased by 60% by exposure to high air temperature and high air humidity during breeding.		
	French Uplands	Annual grassland production system significantly reduced by 4-year exposure to climatic conditions.	A2 2070	Cantarel et al. (2013)
	France	No impact on dairy yields.	A2 1970–1999, 2020–2049, 2070–2099 ARPEGE	Graux et al. (2011)
	Ireland, France	Grassland dairy system increases potential of dairy production, with increased risk of summer–autumn forage failure in France.	A1B By the end of century	
	Overall Europe	Spread of bluetongue virus (BTV) in sheep and ticks in cattle due to climate warming.	2080	Graux et al. (2011)
		No increase in risk of incursion of Crimean–Congo hemorrhagic fever virus in livestock.		Section 23.4.2
Australia	Northern Australia	3°C increase in temperature will result in 21% reduction in forage production for CO_2 at 350 ppm level and no change at 650 ppm level. Changes of ±10% in rainfall were exacerbated to ±15% change in forage production at 350 ppm CO_2.	A1B 2030	McKeon et al. (2009)
	Australia (other than Tasmania)	Dairy output will decline under 1°C increase in temperature.	A1B 2030	Section 25.7.2.1
	25 sites in southern Australia	Profitability of fodder supply production declinedat most sites due to shorter growing season.	A2 2050	
	Southern Australia	Decline in NPP of grassland from historical climate will be 9% in 2030, 7% in 2050, and 14% in 2070. Declines in ANPP were larger at lower rainfall locations. Operating profit (at constant prices) fell by an average of 27% in 2030, 32% in 2050, and 48% in 2070.	A2 2030, 2050, 2070	Moore and Ghahramani (2013)
	Tasmania	Dairy yields increase 0.5–6.2%	A1B, ECHAM5/MPI-OM 2050	Hanslow et al. (2014)
	Victoria	Dairy yields decrease 1.3–6.7%		
	New South Wales	Dairy yields decrease 1.4–6.6%		
	Southern Australia	Dairy yields decrease 2.2–8.1%		
	New Zealand	Change in agricultural production: • Dairy: –2.8%, –4.3% • Sheep and beef: –6.1%, –8.8%	2030 Global temperature change 25%, 75% of the way between lower and upper bounds of scenarios in IPCC 2001 Third Assessment Report.	Wratt et al. (2008)

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Box 7-1 (continued)

Region	Sub-region	Climate change impacts	Scenarios	Reference
Central and South America	Andean Mountain countries	Beef and dairy cattle, pigs, and chickens could decrease between 0.9 and 3.2% while sheep could increase by 7%.	2060 Hot and dry scenario	Section 27.3.4.1
	Colombia, Venezuela, and Ecuador	Beef cattle choice declined.	2060 Milder and wet scenario	
	Argentina and Chile	Beef cattle choice increased.	Future climate change	
	Pernambuco, Brazil	Milk production and feed intake in cattle strongly affectetd.	Future climate change	Silva et al. (2009)
North America	Central United States	Dairy yields decrease 16–30%.	Baseline CO_2, 2× CO_2, 3× CO_2 CGCMI/Hadley	Mader et al. (2009)

pathogens may decrease in lowland tropical areas as temperatures increase (Mills et al., 2010). The temperate regions may become more suitable for tropical vector-borne diseases such as Rift Valley fever and malaria, which are highly sensitive to climatic conditions (Rocque et al., 2008). Vector-borne diseases of livestock such as African horse sickness and bluetongue may expand their range northward to the Northern Hemisphere because rising temperatures increase the development rate and winter survival of vectors and pathogens (Lancelot et al., 2008). Diseases such as West Nile virus and schistosomiasis are projected to expand into new areas (Rosenthal, 2009). The distribution, composition, and migration of wild bird populations that harbor the genetic pool of avian influenza viruses will all be affected by climate change, although in ways that are somewhat unpredictable (Gilbert et al., 2008). The changing frequency of extreme weather events, particularly flooding, will affect diseases too. For example, outbreaks of Rift Valley fever in East Africa are associated with increased rainfall and flooding due to ENSO events (Gummow, 2010; Pfeffer and Dobler, 2010). In general, the impacts of climate change on livestock diseases remain difficult to predict and highly uncertain (Mills et al., 2010; Tabachnick, 2010).

Box 7-1 summarizes impacts on a regional basis for crops and livestock. Developing countries rely heavily on climate-dependent agriculture and especially in conjunction with poverty and rapid increase in population they are vulnerable to climate change. While food insecurity is concentrated mostly in developing countries situated in the tropics (St. Clair and Lynch, 2010; Ericksen et al., 2011; Berg et al., 2013) global food supply may also be affected by heat stress in both temperate and subtropical regions (Teixeira et al., 2013). Chapter 22 identifies Africa as one of the regions most vulnerable to food insecurity. Climate change will also affect crop yields, food security, and local economies in Central America, northeast Brazil, and parts of the Andean region (Chapter 27) as well as in South Asia (Iqbal et al., 2009; see also Chapter 24). As shown in Box 7-1, in spite of uncertainties in responses at regional/national and subnational level, there is *high confidence* that most developing countries will be negatively affected by climate change in the future, although climate change may have positive effects in some regions. In high latitudes (such as Russia, northern Europe, Canada, South America) global warming may increase yields and expand the growing season and acreage of agricultural crops, although yields may be low due to poor soil fertility and water shortages in some regions (Kiselev et al., 2013; see also Chapters 23, 24, 26, 27). Although there is slim evidence, some studies do indicate a significant increase in crops yields in some parts of China, Africa, and India. Like crops, livestock are also negatively affected by climate change in almost all the continents, as evidenced by the regional chapters of Working Group II. The dairy, meat, and wool systems primarily rely on fodders, grasslands, and rangelands. Climate change can impact the amount and quality of produce, profitability, and reliability of production (Chapters 23, 25). Higher temperature would lead to decline in dairy production, reduced animal weight gain, stress on reproduction, increased cost of production, and lower food conversion efficiency in warm regions. Disease incidence among livestock is expected to be exacerbated by climate change as most of the diseases are transmitted by vectors such as ticks and flies (Chapter 23), whose proliferation depends on climatic parameters of temperature and humidity.

7.4.4. Projected Impacts on Food Prices and Food Security

AR4 presented a summary of food price projections based on five studies that used projected yield impacts as inputs to general or partial equilibrium models of commodity trade. Many additional projections of this type have been made since AR4, expanding the number of trade models used, the diversity of yield projections considered, and the disaggregation of prices by commodity (Hertel et al., 2010; Calzadilla et al., 2013; Lobell et al., 2013b; Nelson et al., 2013). Many of the studies did not include CO_2 effects, which is sometimes justified on the grounds that studies are concerned with "worst-case" scenarios, or that the bias from omitting positive CO_2 effects balances the known bias from omitting negative effects of elevated O_3 and increased weed and pest damage. Studies also typically ignore potential changes in yield variability (Figure 7-6) and policy responses such as export bans which have important international price effects (Section 7.2.2).

Based on the studies cited above, it is *very likely* that changes in temperature and precipitation, without considering effects of CO_2, will lead to increased food prices by 2050, with estimated increases ranging from 3 to 84%. The combined effect of climate and CO_2 change (but ignoring O_3 and pest and disease impacts) appears *about as likely as not* to increase prices, with a range of projected impacts from –30% to +45% by 2050. One lesson from recent model intercomparison experiments (Nelson et al., 2014) is that the choice of economic model matters at least as much as the climate or crop model for determining

price response to climate change, indicating the critical role of economic uncertainties for projecting the magnitude of price impacts.

The AR4 concluded that climate changes are expected to result in higher real prices for food past 2050. This conclusion remains intact with *medium confidence*, albeit with a relative lack of new studies exploring price changes to 2100 or beyond. Of course, international prices are only one indicator of global food security, with the pathways by which price changes can affect food security outlined in Section 7.3.3. A limited number of studies have estimated the effects of price changes on food security and related health outcomes. Nelson et al. (2009) project that, without accelerated investment in planned adaptations, climate change by 2050 would increase the number of undernourished children under the age of 5 by 20 to 25 million (or 17 to 22%), with the range including projections with and without CO_2 fertilization. Lloyd et al. (2011) used the projected changes in undernourishment from Nelson et al. (2009) to project the impact of climate change on human nutrition, estimating a relative increase in moderate stunting of 1 to 29% in 2050 compared with a future without climate change. Severe stunting was projected to increase by 23% (central Africa) to 62% (South Asia).

In summary, if global yields are negatively impacted by climate change, an increase in both international food prices and the global headcount of food-insecure people is expected (*limited evidence*, *high agreement*). However, it is only *about as likely as not* that the net effect of climate and CO_2 changes on global yields will be negative by 2050, but *likely* that such changes will occur later in the 21st century. At the same time, it is *likely* that socioeconomic and technological trends, including changes in institutions and policies, will remain a relatively stronger driver of food security over the next few decades than climate change (Goklany, 2007; Parry et al., 2009). Importantly, all of the studies that project price impacts assume some level of on-farm agronomic adaptation, often by optimizing agronomic practices within the model. Most, but not all, also prescribe income growth rates as exogenous factors, despite the fact that incomes are heavily dependent on agriculture in many poor countries. One study that accounted for income effects found that, in countries such as Indonesia that had both a large share of poverty in agriculturally dependent households and yield impacts that were small relative to other regions, poverty was reduced by the effects of climate change (Hertel et al., 2010). However, in most countries the positive income effects of higher prices could not outweigh the costs of reduced productivity and higher food prices.

Recent work has also highlighted that productivity in many sectors besides agriculture are significantly influenced by warming, with generally negative effects of warming on economic output in tropical countries (Hsiang, 2010; Dell et al., 2012). Given the importance of incomes to food access, incorporating these effects into future estimates of food security impacts will be important. Conflict is also known to be an important factor in food security (FAO, 2010), and evidence of climate variability effects on conflict risk (Hsiang et al., 2011) indicates a need to also consider this dimension in future work (Chapter 12).

Since the impacts of climate change on food production and food security depends on multiple interacting drivers, the timing of extreme events, which are expected to become more frequent (IPCC, 2012), is critical. Extremes contribute to variability in productivity (Figure 7-6) and can form part of compound events that are driven by common external forcing (e.g., El Niño), climate system feedbacks, or causally unrelated events (IPCC, 2012). Such compound events, where extremes have simultaneous impacts in different regions, may have negative impacts on food security, particularly against the backdrop of increased food price volatility (Figure 7-3). There are very few projections of compound extreme events, and interactions between multiple drivers are difficult to predict. Effective monitoring and prediction, and building resilience into food systems, are likely to be two key tools in avoiding the negative impacts resulting from these interactions (Misselhorn et al., 2010).

7.5. Adaptation and Managing Risks in Agriculture and Other Food System Activities

7.5.1. Adaptation Needs and Gaps Based on Assessed Impacts and Vulnerabilities

7.5.1.1. Methods of Treating Impacts in Adaptation Studies—Incremental to Transformational

The pervasiveness of climate impacts on food security and production (Section 7.2), the commitment to future climate change from past GHG emissions (WGI AR5 SPM), and the very high likelihood of additional and likely greater climate changes from future GHG emissions (WGI AR5 SPM) mean that some level of adaptation of food systems to climate change will be necessary. Here we take adaptation to mean reductions in risk and vulnerability through the actions of adjusting practices, processes, and capital in response to the actuality or threat of climate change. This often involves changes in the decision environment, such as social and institutional structures, and altered technical options that can affect the potential or capacity for these actions to be realized. Adaptation can also enhance opportunities from climate change (WGII AR4 Chapter 5; Section 17.2.3). These adaptations will need to be taken in the context of a range of other pressures on food security such as increasing demand as a result of population growth and increasing per capita consumption (Section 7.1).

Following the AR4, the literature on adaptation and food production has increased substantially, although there has been less focus on adaptations to food systems and on value chains: the linked sets of activities that progressively add value as inputs are converted into products the market demands. Many adaptation frameworks or approaches have been published, informing the approach in the AR4 that addressed both autonomous and planned adaptations. Autonomous adaptations are incremental changes in the existing system including through the ongoing implementation of extant knowledge and technology in response to the changes in climate experienced. They include coping responses and are reactive in nature. Planned adaptations are proactive and can either adjust the broader system or transform it (Howden et al., 2010). Adaptations can occur at a range of scales from field to policy. There is an increasing recognition in the literature that while many adaptation actions are local and build on past climate risk management experience, effective adaptation will often require changes in institutional arrangements and policies to strengthen the conditions favorable for effective adaptation

including investment in new technologies, infrastructure, information, and engagement processes (Sections 14.3-4, 15.2.4). Building adaptive capacity by decision makers at all scales (Nelson et al., 2008) is an increasingly important part of the adaptation discourse which has also further addressed costs, benefits, barriers, and limits of adaptation (Adger et al., 2009). The sector-specific nature of many adaptations means that sectors are initially addressed separately below.

7.5.1.1.1. Cropping

Effective adaptation of cropping could be critical in enhancing food security and sustainable livelihoods, especially in developing countries (WGII AR4 Chapter 5; Section 9.4.3.1). There is increasing evidence that farmers in some regions are already adapting to observed climate changes in particular altering cultivation and sowing times, crop cultivars and species, and marketing arrangements (Fujisawa and Koyabashi, 2010; Olesen et al., 2011; see also Section 9.4.3.1), although this response is not ubiquitous (Bryan et al., 2009). There are a large number of potential adaptations for cropping systems and for the food systems of which they are part, many of them enhancements of existing climate risk management and all of which need to be embedded in the wider farm systems and community contexts.

The possibility of extended growing seasons due to higher temperatures increasing growth in cooler months means that changing planting dates is a frequently identified option for cereals and oilseeds provided there is not an increase in drought at the end of the growing season (Krishnan et al., 2007; Deressa et al., 2009; Magrin et al., 2009; Mary and Majule, 2009; Meza and Silva, 2009; Tingem and Rivington, 2009; Travasso et al., 2009; Laux et al., 2010; Shimono et al., 2010; Stöckle et al., 2010; Tao and Zhang, 2010; Van de Geisen et al., 2010; Olesen et al., 2011; Cho et al., 2012). Aggregated across studies, changing planting dates may increase yields by a median of 3 to 17% but with substantial variation (Table 7-2). Early sowing is being facilitated by improvements in machinery and by the use of techniques such as dry sowing (Passioura and Angus, 2010), seedling transplanting, and seed priming and these adaptations can be integrated with varieties with greater thermal time requirements so as to maximize production benefits and to avoid late spring frosts (Tingem and Rivington, 2009; Cho et al., 2012). There can, however, be practical constraints to early sowing such as seedbed condition (van Oort et al., 2012). In some situations early sowing may allow double cropping or intercropping where currently only a single crop is feasible. For example, this could occur for irrigated maize in central Chile (Meza et al., 2008) and the double crop wheat/soybean in the southern pampas of Argentina (Monzon et al., 2007), increasing productivity per unit land although increasing nitrogen and water demand at the same time. However, in Mediterranean climates, early sowing of cereals is dependent on adequate planting rains in autumn and climate projections indicate that this may decrease in many regions (WGI AR5 SPM), limiting the effectiveness of this adaptation and possibly resulting in later sowings than are currently practiced. In such circumstances, use of short duration cultivars could be desirable so as to reduce exposure to end-of-season droughts and high-temperature events (Orlandini et al., 2008; Walter et al., 2010). There is *medium confidence* that optimization of crop varieties and planting schedules appears to be effective adaptations, increasing yields by up to 23% compared with current management when aggregated across studies (*medium evidence*, *high agreement*; Table 7-2). This flexibility in planting dates and varieties according to seasonal conditions could be increasingly important with ongoing climate change (Meza et al., 2008; Deressa et al., 2009) and especially in dealing with projections of increased climate variability (Figure 7-6). Approaches that integrate climate forecasts at a range of scales in some cases are able to better inform crop risk management (Cooper et al., 2009; Baethgen, 2010; Li et al., 2010; Sultana et al., 2010) although such forecasts are not always useable or useful (Lemos and Rood, 2010; Dilling and Lemos, 2011; see also Section 9.4.4).

Warmer conditions may also allow range expansion of cropping activities polewards in regions where low temperature has been a past limitation (*limited evidence*, *medium agreement*) provided varieties with suitable daylength response are available and soil and other conditions suitable. This may particularly occur in Russia, Canada, and the Scandinavian nations although the potential may be less than earlier analyses indicated

Frequently Asked Questions

FAQ 7.3 | How could adaptation actions enhance food security and nutrition?

More than 70% of agriculture is rain fed. This suggests that agriculture, food security, and nutrition are all highly sensitive to changes in rainfall associated with climate change. Adaptation outcomes focusing on ensuring food security under a changing climate could have the most direct benefits on livelihoods, which have multiple benefits for food security, including enhancing food production, access to markets and resources, and reduced disaster risk. Effective adaptation of cropping can help ensure food production and thereby contribute to food security and sustainable livelihoods in developing countries, by enhancing current climate risk management. There is increasing evidence that farmers in some regions are already adapting to observed climate changes, in particular altering cultivation and sowing times and crop cultivars and species. Adaptive responses to climate change in fisheries could include management approaches and policies that maximize resilience of the exploited ecosystems, ensuring fishing and aquaculture communities have the opportunity and capacity to respond to new opportunities brought about by climate change, and the use of multi-sector adaptive strategies to reduce the consequence of negative impacts in any particular sector. However, these adaptations will not necessarily reduce all of the negative impacts of climate change, and the effectiveness of adaptations could diminish at the higher end of warming projections.

Table 7-2 | The simulated median benefit (difference between the yield change from baseline for the adapted and non-adapted cases) for different crop management adaptations: cultivar adjustment; planting date adjustment; adjusting planting date in combination with cultivar adjustment; adjusting planting date in combination with other adaptations; irrigation optimization; fertilizer optimization; other management adaptations. N represents the number of estimates used for each adaptation. The numbers in parentheses are the 25th and 75th percentiles. Data points where assessed benefits of management changes are negative are not included as farmers are unlikely to adopt these intentionally. Only studies with both a "no adaptation" and an "adaptation" assessment are used. Data taken from Rosenzweig et al. (1994); Karim et al. (1996); El-Shaher et al. (1997); Lal et al. (1998); Moya et al. (1998); Yates and Strzepek (1998); Alexandrov (1999); Kaiser (1999); Reyenga et al. (1999); Southworth et al. (2000); Tubiello et al. (2000); DeJong et al. (2001); Aggarwal and Mall (2002); Alexandrov et al. (2002); Corobov (2002); Easterling et al. (2003); Matthews and Wasmann (2003); Droogers (2004); Howden and Jones (2004); Butt et al. (2005); Erda et al. (2005); Ewert et al. (2005); Gbetibouo and Hassan (2005); Xiao et al. (2005); Zhang and Liu (2005); Abraha and Savage (2006); Challinor et al. (2009); Tingem and Rivington (2009); Thornton et al. (2010); Deryng et al. (2011); Lal (2011); Tao and Zhang (2011b).

Management option	Cultivar adjustment (N = 56)	Planting date adjustment (N = 19)	Planting date and cultivar adjustment (N = 152)	Irrigation optimization (N = 17)	Fertilizer optimization (N = 10)	Other (N = 9)
Benefit (%) from using adaptation	23 (6.8, 35.9)	3 (2.1, 8.3)	17 (9.9, 26.1)	3.2 (2, 8.2)	1 (0.25, 4.8)	6.45 (3.2, 12.8)

owing to increased climate extremes, water limitations, and various institutional barriers (Alcamo et al., 2007; Bindi and Olesen, 2011; Dronin and Kirilenko, 2011; Kulshreshtha, 2011; Kvalvik et al., 2011; Tchebakova et al., 2011). In many of these cases, the northerly range expansion may only offset the reduction in southerly cropping areas and yields due to lower rainfall, water shortages, and high temperatures (*limited evidence*, *high agreement*).

Improving cultivar tolerance to high temperature is a frequently identified adaptation for almost all crops and environments worldwide as high temperatures are known to reduce both yield and quality (Krishnan et al., 2007; Challinor et al., 2009; Luo et al., 2009; Wassmann et al., 2009; Shimono et al., 2010; Stöckle et al., 2010), noting that a new cultivar usually takes between 8 and 20 years to deliver and so it is important to be selecting cultivars for expected future climate and atmospheric conditions (Ziska et al., 2012). Improving gene conservation and access to extensive gene banks could facilitate the development of cultivars with appropriate thermal time and thermal tolerance characteristics (Mercer et al., 2008; Wassmann et al., 2009) as well as to take advantage of increasing atmospheric CO_2 concentrations (Ziska et al., 2012) and respond to changing pest, disease, and weed threats with these developments needing to be integrated with *in situ* conservation of local varieties (IAASTD, 2009).

Similarly, the prospect of increasing drought conditions in many cropping regions of the world (Olesen et al., 2011) raises the need for breeding additional drought-tolerant crop varieties (Naylor et al., 2007; Mutekwa, 2009; Tao and Zhang, 2011a), for enhanced storage and access to irrigation water, more efficient water delivery systems, improved irrigation technologies such as deficit irrigation, more effective water harvesting, agronomy that increases soil water retention through practices such as minimum tillage and canopy management, agroforestry, increase in soil carbon, and more effective decision support (Verchot et al., 2007; Lioubimtseva and Henebry, 2009; Luo et al., 2009; Falloon and Betts, 2010; Piao et al., 2010; Olesen et al., 2011), among many other possible adaptations (Sections 22.4.2, 22.4.3). There is *medium confidence* (*limited evidence*, *high agreement*) that crop adaptations can lead to moderate yield benefits (mean of 10 to 20%) under persistently drier conditions (Deryng et al., 2011) and that irrigation optimization for changed climate can increase yields by a median of 3.2% (Table 7-2) as well as having a range of other beneficial effects (Section 3.7).

Diversification of activities is another climate adaptation option for cropping systems (Lioubimtseva and Henebry, 2009; Thornton et al., 2010). For example, Reidsma and Ewert (2008) found that regional farm diversity reduces the risk that is currently associated with unfavorable climate conditions in Europe. Diversification of activities often incorporates higher value activities or those that increase efficiency of a limited resource such as through increased water use efficiency (Thomas, 2008) or to reduce risk (Seo and Mendelsohn, 2008; Seo, 2010; Seo et al., 2010). In some cases, increased diversification outside of agriculture may be favored (Coulthard, 2008; Mary and Majule, 2009; Mertz et al., 2009a,b).

The above adaptations, either singly or in combination, could significantly reduce negative impacts of climate change and increase the benefit of positive changes as found in WGII AR4 Chapter 5 (*medium evidence*, *high agreement*). To quantify the benefits of adaptation, a meta-analysis of recent crop adaptation studies has been undertaken for wheat, rice, and maize (see Figure 7-4). This meta-analysis adds more recent studies to that undertaken in the WGII AR4 Chapter 5. It indicates that the average benefit (the yield difference between the adapted and non-adapted cases) of adapting crop management is equivalent to about 15 to 18% of current yields (Figure 7-8). This response is, however, extremely variable, ranging from negligible benefit from adaptation (even potential dis-benefit) to very substantial. The responses are dissimilar between wheat, maize, and rice (Figure 7-4) with temperate wheat and tropical rice showing greater benefits of adaptation. The responses also differ markedly between adaptation management options (Table 7-2). For example, when aggregated over studies, cultivar adaptation (23%) and altering planting date in combination with other adaptations (3 to 17%) provide on average more benefit than optimizing irrigation (3.2%) or fertilization (1%) to the new climatic conditions. These limits to yield improvements from agronomic adaptation and the increasingly overall negative crop yield impact with ongoing climate change (Figures 7-4, 7-5) mean a substantial challenge in ensuring increases in crop production of 14% per decade given a population of 9 billion people in 2050. This could be especially so for tropical wheat and maize, where impacts from increases in temperature of more than 3°C may more than offset benefits from agronomic adaptations (*limited evidence*, *medium agreement*).

Potential increased variability of crop production means that other climate-affected aspects of food systems such as food reserve, storage, and distribution policies and systems may need to be enhanced (IAASTD,

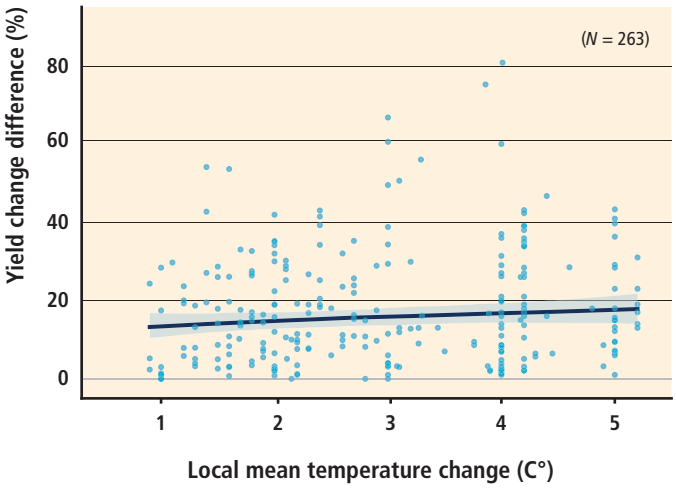


Figure 7-8 | Simulated yield benefit from adaptation calculated as the difference between the yield change from baseline (%) for paired non-adapted and adapted cases as affected by temperature and aggregated across all crops. The shaded bands at the 95% confidence interval are calculated as for Figure 7-4. Data points ($N = 31$) where assessed benefit of management changes are negative are not included as farmers are unlikely to intentionally adopt these. Data sources are the same as for Table 7-2 and only studies that examine both a "no adaptation" and an "adaptation" scenario are used so as to avoid the issues arising from unpaired studies documented in Figure 7-4 for tropical maize.

2009; Stathers et al., 2013) (*medium evidence*, *high agreement*) along with a range of broader, value-chain issues such as provision of effective insurance markets, clarity in property rights, building adaptive capacity, and developing effective participatory research cultures (Chapter 9; WGII AR4 Chapter 5).

It is notable that most of the above adaptations raised above and used in this analysis are essentially either incremental changes to existing agricultural systems or are systemic changes that integrate new aspects into current systems. Few could be considered to be transformative changes. Consequently, the potential adaptation benefits could be understated (*limited evidence*, *medium agreement*; Rickards and Howden, 2012).

7.5.1.1.2. Fisheries

Many of the resources for capture fisheries are already fully or overexploited, with an estimated 30% of stocks overexploited in 2009 and 57% fully exploited (FAO, 2012). Comparable global statistics are not available for inland fisheries but the status of those stocks may not be any better. Overfishing is widely regarded as the primary pressure on marine fishery resources but other human activities including coastal and offshore mining, oil and gas extraction, coastal zone development, land-based pollution, and other activities are also negatively impacting stock status and production (Rosenberg and Macleod, 2005; Cochrane et al., 2009). In inland fisheries, overfishing is also widespread, coupled with many other impacts from other human activities (Allan et al., 2005). Climate change adds another compounding influence in both cases.

Adaptive responses to reduce the vulnerability of fisheries and fishing communities could include management approaches and policies that strengthen the livelihood asset base; improved understanding of the existing response mechanisms to climate variability to assist in adaptation planning; recognizing and responding to new opportunities brought about by climate change; monitoring biophysical, social, and economic indicators linked to management and policy responses; and adoption of multi-sector adaptive strategies to minimize negative impacts (Allison et al., 2009; Badjeck et al., 2010; MacNeil et al., 2010). Complementary adaptive responses include occupational flexibility, changing target species and fishing operations, protecting key functional groups, and the establishment of insurance schemes (Coulthard, 2008; Daw et al., 2009; FAO, 2009a; MacNeil et al., 2010; Koehn et al., 2011). Fishers and fish farmers will be vulnerable to extreme events such as flooding and storm surges that will require a range of adaptations including developing early warning systems for extreme events, provision of hard defenses against flooding and surges, ensuring infrastructure such as ports and landing sites are protected, effective disaster response mechanisms, and others (Daw et al., 2009).

Governance and management of fisheries will need to follow an ecosystem approach to maximize resilience of the ecosystem, and to be adaptive and flexible to allow for rapid responses to climate-induced change (Daw et al., 2009; FAO, 2009a; see also Section 6.4.2). Within an ecosystem approach, habitat restoration will frequently be a desirable adaptation option, particularly in freshwater and coastal environments (Koehn et al., 2011). A wide range of management tools and strategies have been developed to manage fisheries. These are all necessary but not sufficient for adaptation to climate change in fisheries (Grafton, 2010). Grafton argued that the standard tools for fisheries management were developed to control fishing mortality and to maintain adequate levels of recruitment to fishery stocks but without necessarily addressing the needs for resilience to change or to be able to function under changing climates. He therefore proposed that these conventional management tools must be used within processes that (1) have a core objective to encourage ecosystems that are resilient to change and (2) explicitly take into account uncertainties about future conditions and the effect of adaptation, and make use of models to explore the implications of these (Grafton, 2010). There are also opportunities for fisheries to contribute to mitigation efforts (FAO, 2009a; Grafton, 2010).

Aquaculture is the fastest-growing animal-food-producing sector with per capita consumption of products increasing at an average rate of 7.1% per year between 1980 and 2010 (FAO, 2012). Adaptive responses in aquaculture include use of improved feeds and selective breeding for higher temperature tolerance strains to cope with increasing temperatures (De Silva and Soto, 2009) and shifting to more tolerant strains of molluscs to cope with increased acidification (Huppert et al., 2009). Better planning and improved site selection to adapt to expected changes in water availability and quality; integrated water use planning that takes into account the water requirements and human benefits of fisheries and aquaculture in addition to other sectors; and improving the efficiency of water use in aquaculture operations are some of the other adaptation options (De Silva and Soto, 2009).

Integrated water use planning will require making trade-offs between different land and water uses in the watershed (Mantua et al., 2010). Insurance schemes accessible to small-scale producers would help to increase their resilience (De Silva and Soto, 2009). In some near-shore

locations there may be a need to shift property lines as the mean high water mark is displaced landwards by rising sea level (Huppert et al., 2009).

There are no simple, generic recipes for fisheries adaptation with Bell et al. (2011) suggesting a list of 25 separate but inter-related actions, together with supporting policies to adapt fisheries and aquaculture in the tropical Pacific to climate change (see also Section 30.6.2.1.1). These actions fall into three categories according to the primary objective: economic development and government revenue; maintaining the contribution of fish to food security; and maximizing sustainable livelihoods. Actions and policies for adaptation in fisheries and aquaculture must complement those for other sectors. Similar case-by-case, integrated planning will be required in all other regions and at scales from community to regional to achieve clearly defined adaptation goals.

7.5.1.1.3. Livestock

Extensive livestock systems occur over a huge range of biophysical and socio-ecological systems, with a consequent large range of potential adaptations. In many cases, these livestock systems are highly adapted to past climate risk, and there is *high confidence* that this provides a sound starting point for climate change adaptation (*medium evidence, high agreement*; Thornton et al., 2009a). These adaptations include matching stocking rates with pasture production; adjusting herd and watering point management to altered seasonal and spatial patterns of forage production; managing diet quality (using diet supplements, legumes, choice of introduced pasture species and pasture fertility management); more effective use of silage, pasture spelling, and rotation; fire management to control woody thickening; using more suitable livestock breeds or species; migratory pastoralist activities; and a wide range of biosecurity activities to monitor and manage the spread of pests, weeds, and diseases (Fitzgerald et al., 2008; Howden et al., 2008; Nardone et al., 2010; Ghahramani and Moore, 2013; Moore and Ghahramani, 2013). Combining adaptations can result in substantial increases in benefits in terms of production and profit when compared with single adaptations (Ghahramani and Moore, 2013; Moore and Ghahramani, 2013). In some regions, these activities can in part be informed by climate forecasts at differing time scales to enhance opportunities and reduce risks including soil degradation (McKeon et al., 2009). Many livestock systems are integrated with or compete for land with cropping systems and one climate adaptation may be to change these relationships. For example, with increased precipitation, farmers in Africa may need to reduce their livestock holdings in favor of crops, but with rising temperatures, they may need to substitute small ruminants in place of cattle with small temperature increases or reduce stocking rates with larger temperature rises (Kabubo-Mariara, 2009; Thornton et al., 2010). As with other food systems there is a range of barriers to adaptation that could be addressed on-farm and off-farm by changes in infrastructure, establishment of functioning markets, improved access to credit, improved access to water and water management technologies, enhanced animal health services, and enhanced knowledge adoption and information systems (Howden et al., 2008; Kabubo-Mariara, 2008; Mertz et al., 2009b, Silvestri et al., 2012).

Heat stress is an existing issue for livestock in some regions (*robust evidence*, *high agreement*), especially in higher productivity systems (Section 7.3.2.6). For example, some graziers in Africa are already making changes to stock holdings in response to shorter term variations in temperatures (Thornton et al., 2009a; see also 9.4.3.1). Breeding livestock with increased heat stress resistance is an adaptation often identified but there are usually trade-offs with productivity as well as benefits including animal welfare and so this option needs careful evaluation (Nardone et al., 2010). Increased shade provision through trees or cost-effective structures can substantially reduce the incidence of high heat stress days, reduce animal stress, and increase productivity, with spraying a less effective option (Gaughan et al., 2010; Nidumolu et al., 2013). In cooler climates, warming may be advantageous because of lesser need for winter housing and feed stocks.

7.5.1.1.4. Indigenous knowledge

Indigenous knowledge (IK) has developed to cope with climate hazards contributing to food security in many parts of the world. Examples in the Americas include Alaska, where the Inuit knowledge of climate variability ensured the source of food to hunters and reduced various risks (Alessa et al., 2008; Ford, 2009; Weatherhead et al., 2010) down to the southern Andes, where the Inca traditions of crop diversification, genetic diversity, raised bed cultivation, agroforestry, weather forecasting, and water harvesting are still used in agriculture (Goodman-Elgar, 2008; Renard et al., 2011; McDowell and Hess, 2012; see also Sections 9.4.3.1, 27.3.4.2). In Africa, weather forecasting, diversity of crops and agropastoralism strategies have been useful in the Sahel (Nyong et al., 2007). Rainwater harvesting has been a common practice in sub-Saharan Africa (Biazin et al., 2012) to cope with dry spells and improve crop productivity, while strategies from agropastoralists in Kenya are related to drought forecasting based on the fauna, flora, moon, winds, and other factors (Speranza et al., 2010). In South Africa, farmers' early warming indicators of wet or dry periods in Namibia based on animals, plants, and climate observations contributed to deal with climatic variability (Newsham and Thomas, 2011). In the same way, in Asia and Australia IK plays an important role to ensure food security of certain groups (Salick and Ross, 2009; Green et al., 2010; Marin, 2010; Speranza et al., 2010; Kalanda-Joshua et al., 2011; Pareek and Trivedi, 2011; Biazin et al., 2012), although IK and the opportunities to implement it can differ according to gender and age in some communities (Rengalakshmi, 2007; Turner and Clifton, 2009; Kalanda-Joshua et al., 2011; see also Section 9.3.5), leading to distinct adaptive capacities and options.

In addition to changes already occurring in climate (seasonal changes, changes in extreme events; IPCC 2012) projected changes beyond historical conditions could reduce the reliance on indigenous knowledge (Speranza et al., 2010; Kalanda-Joshua et al., 2011; McDowell and Hess, 2012) affecting the adaptive capacity of a number of peoples globally (*medium evidence*, *medium agreement*).

Moreover, there is *medium confidence* that some policies and regulations leading to limit the access to territories, promoting sedentarization, the substitution of traditional livelihoods, reduced genetic diversity and harvesting opportunities, as well as loss of transmission of indigenous knowledge, may contribute to limit the adaptation to climate change in many regions (*medium evidence*, *medium agreement*; Nakashina et al., 2012).

7.5.1.2. Practical Regional Experiences of Adaptation, Including Lessons Learned

Given the early stages of climate change, there are relatively few unequivocal examples of adaptation (Section 7.5.2) additional to existing climate risk management. Where there have been management changes these have often been in response to several driving variables of which climate is only one (Smit and Wandel, 2006; Mertz et al., 2009a; Chen et al., 2011; Odgaard et al., 2011; see also Section 9.4.3.1). The preparedness to consider adaptation even within an industry varies regionally (Battaglini et al., 2009) and in some regions there already appears to be adaptation to climate change occurring (Fujisawa and Koyabashi, 2010; Olesen et al., 2011; Bohensky et al., 2012; Section 9.4.3.1). Activities to build adaptive capacity to better manage climate change are more widespread (Twomlow et al., 2008) but there remain questions as to how this capacity will evolve and be maintained (Nelson et al., 2009). Crucial in this will be devolution of the decision-making process so as to integrate local, contextual information into adaptation decision making (Nelson et al., 2008).

7.5.1.3. Observed and Expected Barriers and Limits to Adaptation

Adaptation is strongly influenced by factors including institutional, technological, informational, and economic and there can be barriers (restrictions that can be addressed) and limits in all these factors (*robust evidence*, *high agreement*; Chapters 14, 15, 16). Several barriers to adaptation of food systems have been raised including inadequate information on the climate and climate impacts and on the risks and benefits of the adaptation options, lack of adaptive capacity, inadequate extension, institutional inertia, cultural acceptability, financial constraints including access to credit, insufficient fertile land, infrastructure, lack of functioning markets, and insurance systems (Bryan et al., 2009; Deressa et al., 2009; Kabubo-Mariara, 2009; De Bruin and Dellink, 2011, Silvestri et al., 2012; see also Chapter 16). Limits to adaptation can occur for example where crop yields drop below the level required to sustain critical infrastructure such as sugar or rice mills (Park et al., 2012). In some cases, these can be effectively irreversible. Some studies have shown that access to climate information is not the principal limitation to improving decision making and it can result in perverse outcomes, increasing inequities and widening gender gaps (Coles and Scott, 2009). Incomplete adoption of adaptations may also occur. Lack of technical options can also be a barrier to adaptation. New varieties of crops or breeds of livestock provide possible core adaptations of production systems (*medium evidence*, *high agreement*; Mercer et al., 2008; Tingem and Rivington, 2009); however, there is substantial investment needed to develop these along with delays before they are available, both of which can act as adaptation barriers. This may be addressed in part by investments to improve local crop varieties or livestock breeds that are easily adopted (IAASTD, 2009). There also can be physiological limits to performance such as upper temperature limits for heat tolerance (WGII AR4 Chapter 5).

7.5.1.4. Facilitating Adaptation and Avoiding Maladaptation

Adaptation actions would usually be expected to provide benefits to farmers, the food industry along the value chain, or perhaps to a broader community. However, there are possible maladaptations that arise from adapting too early or too late, by changing the incorrect elements of the food system or changing them by the incorrect amount (Section 14.7). A key maladaptation would be one which increased emissions of GHGs, this making the underlying problem worse (*robust evidence*, *high agreement*; Smith and Olesen, 2010; WGIII AR4 Chapter 11). A recent review of agricultural climate change adaptation options found they tend to reduce GHG emissions (Smith and Olesen, 2010; Falloon and Betts, 2010) (*medium evidence*, *medium agreement*). These adaptations include measures that reduce soil erosion and loss of nutrients such as nitrogen and phosphorus and for increasing soil carbon, conserving soil moisture, and reducing temperature extremes by increasing vegetative cover. There is a strong focus on incremental adaptation of existing food systems in the literature since AR4, however, and this may result in large opportunity costs that could arise from not considering more systemic adaptation or more transformative change (*limited evidence*, *medium agreement*; Howden et al., 2010; Kates et al., 2012). For example, in the USA, changes in farming systems (i.e., the combination of crops) have been assessed as providing significant adaptation benefit in terms of net farm income (Prato et al., 2010) although in other regions this might be minor (Mandryk et al., 2012). There is a need to also engage farmers, policymakers, and other stakeholders in evaluating transformative, pro-active, planned adaptations such as structural changes (Mäder et al., 2006; McCrum et al., 2009; Olesen et al., 2011). This could involve changes in land allocation and farming systems, breeding of functionally different crop varieties, new land management techniques, and new classes of service from lands such as ecosystem services (Rickards and Howden, 2012). In Australia, industries including the wine, rice, and peanut sectors are already attempting transformative changes such as change in location so as to be early adopters of what are perceived as opportunities arising from change (Park et al., 2012). There is substantial commonality in adaptation actions within different agricultural systems. For example, changing varieties and planting times are incremental adaptations found in studies of many different cropping systems as evidenced by the sample size in the meta-analysis in this chapter. Collating information on the array of adaptation options available for farmers, their relative cost and benefit, and their broad applicability could be a way of initiating engagement with decision makers. In the climate mitigation domain, this has been attempted using marginal abatement cost curves that identify mitigation options, their relative cost, and the potential size of emission reductions (WGIII AR4 Chapter 11). These curves can be used in setting investment priorities and informing policy discussions. The local nature of many adaptation decisions, their interactions with other highly contextual driving factors, and the time and climate change-sensitive nature of adaptation decisions mean, however, that global, time-independent curves are not feasible. The studies aggregated in Table 7-2 indicate that some options may be more relevant and useful to consider than others. These results illustrate the potential scope and benefit of developing effective adaptation options if implemented in an adaptive management approach.

7.5.2. Food System Case Studies of Adaptation—Examples of Successful and Unsuccessful Adaptation

Incremental, systemic, and transformational adaptation to climate change is beginning to be documented, though the peer-reviewed

literature largely covers vulnerability assessments and intentions to act, not adaptation actions (Berrang-Ford et al., 2010).

Case 1: Incremental Adaptation in the Sahel

Much of the literature covers incremental, reactive adaptation, but given actors are constantly adapting to changing social and economic conditions, incremental adaptation to climate change is difficult to distinguish from other actions (Berrang-Ford et al., 2010; Speranza et al., 2010), and in fact is usually a response to a complex of factors. This case, of the zaï soil management practice in the Sahel region, is an example of a complex of factors driving local actions, and factors such as growing land scarcity and new market opportunities, rather than climate, may be the primary factors (Barbier et al., 2009; Mertz, 2009b). Inherent poor soil quality and human activities have resulted in soil degradation—crusting, sealing, erosion by water and wind, and hardpan formation (Fatondji et al., 2009; Zougmoré et al., 2010). Zaï, a traditional integrated soil and water management practice, can combat land degradation and improve yield and decrease yield variability by concentrating runoff water and organic matter in small pits (20 to 40 cm in diameter and 10 to 15 cm deep) dug manually during the dry season and combined with contour stone bunds to slow runoff. A handful of animal manure or compost is placed in each pit. By breaking the soil crust, the pits facilitate greater water infiltration, while the applied organic matter improves soil nutrient status and attracts termites, which have a positive effect on soil structure. The zaï technique is very labor intensive, requiring some 60 days of labor per hectare. Innovations to the system, involving animal-drawn implements, can reduce labor substantially.

Case 2: Mixed Farming Systems in Tanzania

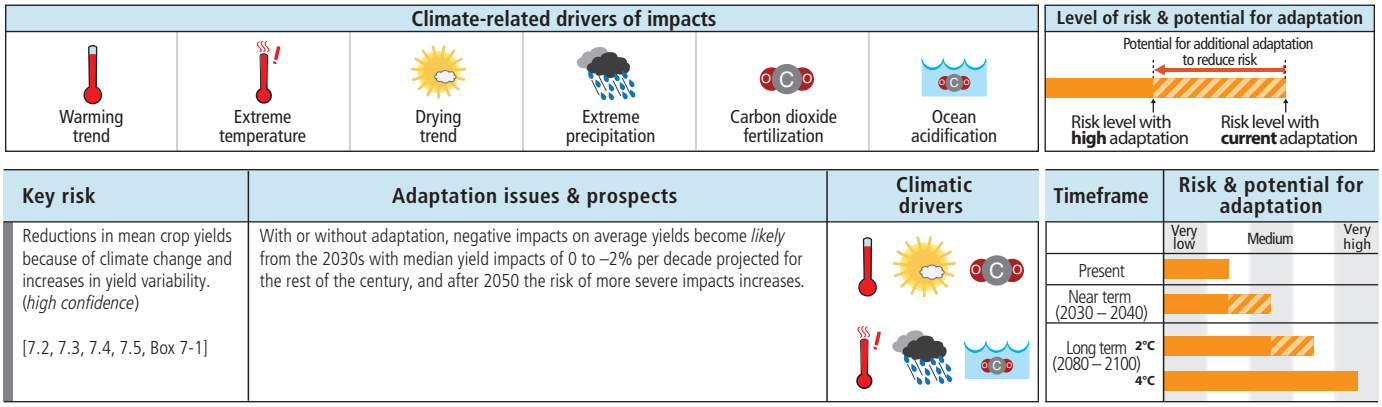
In Morogoro, Tanzania, farming households have adapted in many ways to climatic and other stresses (Paavola, 2008). They have extended cultivation through forest clearance or reducing the length of the fallow period. Intensification is under way, through change in crop choices, increased fertilizer use and irrigation, and especially greater labor inputs. Livelihood diversification has been the main adaptation strategy—this has involved more non-farm income-generating activities, tapping into natural resources for subsistence and cash income (e.g., charcoal production), and has included artisanal gold and gemstone mining. Households have also altered their cropping systems, for example, by changing planting times. Migration is another frequently used strategy—with farmers moving to gain land, access to markets, or employment. Parents also send children to cities to work for upkeep and cash income to reduce the household numbers that need to be supported by uncertain agricultural income. While many of these strategies help in terms of the short-term needs, in the longer term they may be reducing the capacity of households to cope. For instance, land cover change interacting with climate changes has negative impacts on current and future water supplies for irrigation (Natkhin et al., 2013), and deforestation and forest degradation means faltering forest-based income sources. This will be particularly problematic to the more vulnerable groups in the community, including women and children.

7.5.3. Key Findings from Adaptations—Confidence Limits, Agreement, and Level of Evidence

There have been many studies of crop adaptation since the AR4. In aggregate these show that adaptations to changed temperature and precipitation will bring substantial benefit (*robust evidence*, *high agreement*), with some adaptations (e.g., cultivar adaptation and planting date adjustment) assessed as on average being more effective than others (e.g., irrigation optimization; Section 7.5.1.1.1). Most studies have assessed key farm-level adaptations such as changing planting dates and associated decisions to match evolving growing seasons and improving cultivar tolerance to high temperature, drought conditions, and elevated CO_2 levels. Limits to adaptation will increasingly emerge for such incremental adaptations as the climate further changes, raising the need for more systemic or transformational changes (*limited evidence*, *medium agreement*; Section 7.5.1.1). An example of transformational change is latitudinal expansion of cold-climate cropping zones polewards, but this may be largely offset by reductions in cropping production in the mid-latitudes as a result of rainfall reduction and temperature increase (*medium confidence*, *limited evidence*; Section 7.5.1.1.1). Adaptations to food systems additional to the production phase have been identified and sometimes implemented but the benefits of these have largely not been quantified.

Livestock and fisheries systems also have available a large range of possible adaptations often tailored to local conditions but there is not adequate information to aggregate the possible value of these adaptations although there is *high confidence* (*medium evidence*, *high agreement*) that they will bring substantial benefit, particularly if implemented in

Table 7-3 | Schematic key risks for food security and the potentials for adaptation in the near and long term for high and low levels of warming.



combination (Sections 7.5.1.1.2-3). Key livestock adaptations include matching stocking rates with pasture availability; water management; monitoring and managing the spread of pests, weeds, and diseases; livestock breeding; and adjusting to changed frequencies of heat stress and cold conditions (Section 7.5.1.1.3). Fishery adaptations include management approaches and policies that strengthen the livelihood asset base, take a risk-based ecosystem approach to managing the resource, and adopt multi-sector adaptive strategies to minimize negative impacts. Importantly, there is an emerging recognition that existing fishery management tools and strategies are necessary but not sufficient for adaptation to climate (Section 7.5.1.1.2).

Indigenous knowledge is an important resource in climate risk management and is important for food security in many parts of the world. Climate changes may be reducing reliance on indigenous knowledge in some locations but also some policies and regulation may be limiting the contribution that indigenous knowledge can make to effective climate adaptation (*medium evidence*, *medium agreement*; Section 7.5.1.1.4).

The focus on incremental adaptations and few studies on more systemic and transformational adaptation or adaptation across the food system mean that there may be underestimation of adaptation opportunities and benefits (*limited evidence*, *medium agreement*; Section 7.5.1.1). In addition to this, there is a range of limits and barriers to adaptation and many of these could be addressed by devolution of the decision-making process so as to integrate local, contextual information into adaptation decision making. A schematic summary of these issues is given in Table 7-3.

7.6. Research and Data Gaps—Food Security as a Cross-Sectoral Activity

Research and data gaps reflect that most work since AR4 has continued to concentrate on food production and has not included other aspects of the food system that connect climate change to food security. Features such as food processing, distribution, access, and consumption have recently become areas of research interest in their own right but only tangentially attached to climate change.

Many studies either do not examine yield variability or do not report it. Closer attention should be paid to yield variability in the quantity and quality of food production, especially given observed price fluctuations associated with climate events. We expect environmental thresholds and tipping points, such as high temperatures, droughts, and floods, to become more important in the future. Specific recommendations are for food production experiments in which changes in variability reflect predicted changes for given warming scenarios. Including thresholds in impact models, for especially high levels of global warming (i.e., 4 to 6°C above preindustrial), are highly likely to result in lower projections of yield, given changes in climate variability and increasing mean temperatures. Important gaps in knowledge continue to be studies of weeds, pests, and diseases, including animal diseases, in response to climate change and how related adaptation activities can be robustly incorporated into food security assessments. Yield and other agronomic data, at a range of spatial scales, are crucial to the development, evaluation, and improvement of models. Model development is currently limited by lack of data.

Adaptation studies for cropping systems typically assess relatively minor agronomic management changes under future climate conditions only. Forthcoming studies should examine the impact of proposed adaptations when employed in the current climate. In this way management changes that are beneficial in a range of environments can be separated from management changes that are specifically targeted at climate change. Further, studies should be inclusive of the broader range of systemic and transformational adaptation options open to agriculture.

Current forecasts of changes in distribution and productivity of marine fish species and communities are typically at a global or regional scale and include adaptations to only a limited extent. Increasing the resolution to forecast impacts and changes at the national and local ecosystem scale would provide valuable information to governments and stakeholders and enable them to prepare more effectively for expected impacts on food production and security offered by fisheries.

Possibilities for agronomic and breeding adaptations of food production to global warming are possible up to high levels of climate change. However, food security studies are urgently required to estimate the actual range of adaptations open to farmers and other actors in the food system and the implementation paths for these, especially when possible changes in climate variability are included.

References

Abraha, M.G. and M.J. Savage, 2006: Potential impacts of climate change on grain yield of maize for the midlands of KwaZulu-Natal, South Africa. *Agriculture Ecosystems and Environment*, **115(1-4)**, 150-160.

Abou-Hadid, A.F., 2006: *Assessment of Impacts, Adaptation, and Vulnerability to Climate Change in North Africa: Food Production and Water Resources*. AIACC Final Report Project No. AF 90, Washington, DC, USA, 128 pp.

Adger, W., S. Dessai, M. Goulden, M. Hulme, I. Lorenzoni, D. Nelson, L. Naess, J. Wolf, and A. Wreford, 2009: Are there social limits to adaptation to climate change? *Climatic Change*, **93(3-4)**, 335-354.

Aggarwal, P.K. and R.K. Mall, 2002: Climate change and rice yields in diverse agro-environments of India. II. Effect of uncertainties in scenarios and crop models on impact assessment. *Climatic Change*, **52(3)**, 331-343.

Ainsworth, E.A. and J.M. McGrath, 2010: Direct effects of rising atmospheric carbon dioxide and ozone on crop yields. In: *Climate Change and Food Security: Adapting Agriculture to a Warmer World* [Lobell, D. and M. Burke (eds.)]. Springer, Dordrech, Netherlands and New York, NY, USA, pp. 109-130.

Ainsworth, E.A., A. Leakey, D.R. Ort, and S.P. Long, 2008: FACE-ing the facts: inconsistencies and interdependence among field, chamber and modeling studies of elevated CO_2 impacts on crop yield and food supply. *New Phytologist*, **179**, 5-9.

Akhtar, N., M. Yamaguchi, H. Inada, D. Hoshino, T. Kondo, M. Fukami, R. Funada, and T. Izuta, 2010: Effects of ozone on growth, yield and leaf gas exchange rates of four Bangladeshi cultivars of rice (*Oryza sativa* L.). *Environmental Pollution*, **158**, 2970-2976.

Aksoy, A. and A. Isik-Dikmelik, 2008: *Are Low Food Prices Pro-Poor? Net Food Buyers and Sellers in Low-Income Countries*. World Bank Policy Research Working Paper No. 4642, World Bank, Washington DC, USA, 30 pp.

Aksoy, A., J. Beverinotti, K. Covarrubias, and A. Zezza, 2010: Household income structures in low-income countries. In: *Food Prices and Rural Poverty* [Aksoy, M. and B. Hoekstra (eds.)]. World Bank, Washington DC, USA, pp. 89-112.

Al-Bakri, J., A. Suleiman, F. Abdulla, and J. Ayad, 2010: Potential impact of climate change on rainfed agriculture of a semi-arid basin in Jordan. *Physics and Chemistry of the Earth, Parts A/B/C*, **36(5-6)**, 125-134.

Alcamo, J., N. Dronin, M. Endejan, G. Golubev, and A. Kirilenko, 2007: A new assessment of climate change impacts on food production shortfalls and water availability in Russia. *Global Environmental Change*, **17(3-4)**, 429-444.

Alderman, H., 2010: Safety nets can help address the risks to nutrition from increasing climate variability. *Journal of Nutrition*, **140(Suppl. 1)**, 148S-152S.

Alessa, L., A. Kliskey, P. Williams, and M. Barton, 2008: Perception of change in freshwater in remote resource dependent Artic communities. *Global Environmental Change*, **18**, 153-164.

Alexandratos, N. and J. Bruinsma, 2012: *World Agriculture towards 2030/2050: The 2012 Revision*. ESA Working Paper No. 12-03, Agricultural Development Economics Division (ESA), Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 147 pp.

Alexandrov, V., 1999: Vulnerability and adaptation of agronomic systems in Bulgaria. *Climate Research*, **12(2-3)**, 161-173.

Alexandrov, V. and G. Hoogenboom, 2000: The impact of climate variability and change on crop yield in Bulgaria. *Agricultural and Forest Meteorology*, **104(4)**, 315-327.

Alexandrov, V., J. Eitzinger, V. Cajic, and M. Oberforster, 2002: Potential impact of climate change on selected agricultural crops in north-eastern Austria. *Global Change Biology*, **8(4)**, 372-389.

Allan, D.J., R. Abell, Z. Hogan, C. Revenga, B.W. Taylor, R.L. Welcomme, and K. Winemiller, 2005: Overfishing of inland waters. *BioScience*, **55(12)**, 1041-1051.

Allison, E.H., A.L. Perry, M. Badjeck, W. Neil Adger, K. Brown, D. Conway, A.S. Halls, G.M. Pilling, J.D. Reynolds, N.L. Andrew, and N.K. Dulvy, 2009: Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries*, **10**, 173-196.

Ambardekar, A.A., T.J. Siebenmorgen, P.A. Counce, S.B. Lanning, and A. Mauromoustakos, 2011: Impact of field-scale nighttime air temperatures during kernel development on rice milling quality. *Field Crops Research*, **122(3)**, 179-185.

Amthor, J.S., 2001: Effects of atmospheric CO_2 concentration on wheat yield: review of results from experiments using various approaches to control CO_2 concentration. *Field Crops Research*, **73**, 1-34.

André, G., B. Engel, P. Berentsen, T.V. Vellinga, and A. Oude Lansink, 2011: Quantifying the effect of heat stress on daily milk yield and monitoring dynamic changes using an adaptive dynamic model. *Journal of Dairy Science*, **94**, 4502-4513.

Antle, J.M. and C.C. Crissman, 1990: Risk, efficiency, and the adoption of modern crop varieties: evidence from the Philippines. *Economic Development and Cultural Change*, **38(3)**, 517-537.

Anwar, M.R., G. O'Leary, D. McNeil, H. Hossain, and R. Nelson, 2007: Climate change impact on rainfed wheat in south-eastern Australia. *Field Crops Research*, **104(1-3)**, 139-147.

Archambault, D.J., 2007: Efficacy of herbicides under elevated temperature and CO_2. In: *Agroecosystems in a Changing Climate* [Newton, P.C.D., A. Carran, G.R. Edwards, and P.A. Niklaus (eds.)]. CRC Press, Boston, MA, USA, pp. 262-279.

Arndt, C., K. Strzepeck, F. Tarp, J. Thurlow, C. Fant IV, and L. Wright, 2011: Adapting to climate change: an integrated biophysical and economic assessment for Mozambique. *African Regional Perspectives*, **6(1)**, 7-20.

Asseng, S., I. Foster, and N.C. Turner, 2011: The impact of temperature variability on wheat yields. *Global Change Biology*, **17**, 997-1012.

Asseng, S., F. Ewert, C. Rosenzweig, J.W. Jones, J.L. Hatfield, A. Ruane, K.J. Boote, P. Thorburn, R.P. Rötter, D. Cammarano, N. Brisson, B. Basso, P. Martre, P.K. Aggarwal, C. Angulo, P. Bertuzzi, C. Biernath, A.J. Challinor, J. Doltra, S. Gayler, R. Goldberg, R. Grant, L. Heng, J. Hooker, L.A. Hunt, J. Ingwersen, R.C. Izaurralde, K.C. Kersebaum, C. Müller, S.N. Kumar, C. Nendel, G. O'Leary, J.E. Olesen, T.M. Osborne, T. Palosuo, E. Priesack, D. Ripoche, M.A. Semenov, I. Shcherbak, P. Steduto, C. Stöckle, P. Stratonovitch, T. Streck, I. Supit, F. Tao, M. Travasso, K. Waha, D. Wallach, J.W. White, J.R. Williams, and J. Wolf, 2013: Uncertainty in simulating wheat yields under climate change. *Nature Climate Change*, **3(9)**, 827-832.

Auffhammer, M., V. Ramanathan, and J.R. Vincent, 2012: Climate change, the monsoon, and rice yield in India. *Climatic Change*, **111(2)**, 411-424.

Avnery, S., D.L. Mauzerall, J. Liu, and L.W. Horowitz, 2011a: Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage. *Atmospheric Environment*, **45(13)**, 2284-2296.

Avnery, S., D.L. Mauzerall, J. Liu, and L.W. Horowitz, 2011b: Global crop yield reductions due to surface ozone exposure: 2. Year 2030 potential crop production losses and economic damage under two scenarios of O_3 pollution. *Atmospheric Environment*, **45(13)**, 2296-2309.

Badjeck, M., E. Allison, A. Halls, and N. Dulvey, 2010: Impacts on climate variability and change on fishery-based livelihoods. *Marine Policy*, **34(3)**, 375-383.

Baethgen, W.E., 2010: Climate risk management for adaption to climate variability and change. *Crop Science*, **50(2)**, 70-76.

Baldocchi, D. and S. Wong, 2008: Accumulated winter chill is decreasing in the fruit growing regions of California. *Climatic Change*, **87**, 153-166.

Barati, F., B. Agung, P. Wongsrikeao, M. Taniguchi, T. Nagai, and T. Otoi, 2008: Meiotic competence and DNA damage of porcine oocytes exposed to an elevated temperature. *Theriogenology*, **69**, 767-772.

Barbier, B., H. Yacouba, H. Karambiri, M. Zorome, and B. Some, 2009: Human vulnerability to climate variability in the Sahel: farmers' adaptation strategies in northern Burkina Faso. *Environmental Management*, **43**, 790-803.

Battaglini, A., G. Barbeau, M. Bindi, and F. Badeck, 2009: European winegrowers' perception of climate change impact and options for adaption. *Regional Environmental Change*, **9(2)**, 61-73.

Bearchell, S.J., B.A. Fraaije, M.W. Shaw, and B.D. Fitt, 2005: Wheat archive links long-term fungal pathogen population dynamics to air pollution. *Proceedings of the National Academy of Sciences of the United States of America*, **102**, 5438-5442.

Bell, J., M. Batty, A. Ganachaud, P. Gehrke, A. Hobday, O. Hoegh-Guldberg, J. Johnson, R. Le Borgne, P. Lehodey, J. Lough, T. Pickering, M. Pratchett, M. Sheaves, and M. Waycott, 2009: *Preliminary Assessment of the Effects of Climate Change on Fisheries and Aquaculture in the Pacific*. Secretariat of the Pacific Community, Noumea, New Caledonia, 15 pp.

Bell, J., N.L. Andrew, M.J. Batty, L.B. Chapman, J.M. Dambacher, B. Dawson, A.S. Ganachaud, P.C. Gehrke, J. Hampton, A.J. Hobday, O. Hoegh-Guldberg, J.E. Johnson, J.P. Kinch, R. Le Borgne, P. Lehody, J.M. Lough, T.D. Pickering, M.S. Pratchett, A. Vunisea, and M. Waycott. 2011: Adapting tropical Pacific fisheries and aquaculture to climate change: management measures, policies and investments. In: *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change* [Bell, J.D., J.E. Johnson, and A.J. Hobday (eds.). Secretariat of the Pacific Community, Noumea, New Caledonia, pp. 803-876.

Ben Mohamed, A., 2011: Climate change risks in Sahelian Africa. *Regional Environmental Change*, **11(1)**, 109-117.

Bellocchi, G., M. Rivington, M. Donatelli, and K. Matthews, 2010: Validation of biophysical models: issues and methodologies. A review. *Agronomy for Sustainable Development*, **30**, 109-130.

Berg, A., M. de Noblet-Ducoudre, B. Sultan, M. Langaigne, and M. Guimberteau, 2013: Projections of climate change impacts on potential C_4 crop productivity over tropical regions. *Agricultural and Forest Meteorology*, **170**, 89-102.

Bergot, M., E. Cloppet, V. Pérnaud, M. Déqué, B. Marçais, and M. Desprez-Loustau, 2004: Simulation of potential range expansion of oak disease caused by *Phytophthora cinnamomi* under climate change. *Global Change Biology*, **10**, 1539-1552.

Berrang-Ford, L., J. Ford, and J. Paterson, 2010: Are we adapting to climate change? *Global Environmental Change*, **21**, 25-33.

Biazin, B., G. Sterk, M. Temesgen, A. Abdulkedir, and L. Stroosnijder, 2012: Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa – a review. *Physics and Chemistry of the Earth*, **48**, 139-151.

Bindi, M. and J. Olesen, 2011: The responses of agriculture in Europe to climate change. *Regional Environmental Change*, **11(Suppl. 1)**, 151-158.

Bloem, M.W., R. Semba, and K. Kraemer, 2010: Caster Gandolfo Workshop: an introduction to the impact of climate change, the economic crisis and the increases in the food prices on malnutrition. *Journal of Nutrition*, **140(Suppl. 1)**, 132S-135S.

Bohensky, E., A. Smaigl, and T. Brewer, 2012: Patterns in household-level engagement with climate change in Indonesia. *Nature Climate Change*, **3**, 348-351.

Bondeau, A., P.C. Smith, S. Zaehle, S. Schaphoff, W. Lucht, W. Cramer, D. Gerten, H. Lotze-Campen, C. Müller, M. Reichstein, and B. Smith, 2007: Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology*, **13**, 679-706.

Booker, F., R. Muntifering, M. McGrath, K. Burkey, D. Decoteau, E. Fiscus, W. Manning, S. Krupa, A. Chappelka, and D. Grantz, 2009: The ozone component of global change: potential effects on agricultural and horticultural plant yield, product quality and interactions with invasive species. *Journal of Integrative Plant Biology*, **51**, 337-351.

Brander, K., 2007: Global fish production and climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **104**, 19709-19714.

Brander, K., 2010: Impacts of climate change on fisheries. *Journal of Marine Systems*, **79**, 389-402.

Brassard, J.P. and B. Singh, 2007: Effects of climate change and CO_2 increase on potential agricultural production in Southern Québec, Canada. *Climate Research*, **34**, 105-117.

Brassard, J.P. and B. Singh, 2008: Impacts of climate change and CO_2 increase on crop yields and adaptation options for Southern Quebec, Canada. *Mitigation and Adaptation Strategies for Global Change*, **13**, 241-265.

Bridges, D.C., 1992: *Crop Losses Due to Weeds in the United States.* Weed Science Society of America, Champaign, IL, USA, 403 pp.

Brinkman, H.S., S. de Pee, I. Aanogao, L. Subran, and M.W. Bloem, 2010: High food prices and the global financial crisis have reduced access to nutritious food and worsened nutritional status and health. *Journal of Nutrition*, **140(Suppl. 1)**, 153S-161S.

Brisson, N., P. Gate, D. Gouache, G. Charmet, F. Oury, and F. Huard, 2010: Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. *Field Crops Research*, **119**, 201-212.

Brown, C.J., E.A. Fulton, A.J. Hobday, R.J. Matear, H.P. Possingham, C. Bulman, V. Christensen, R.E. Forrest, P.C. Gehrke, N.A. Gribble, S.P. Griffiths, H. Lozano-Montes, J.M. Martin, S. Metcalf, T.A. Okey, R. Watson, and A.J. Richardson, 2010: Effects of climate-driven primary production change on marine food webs: implications for fisheries and conservation. *Global Change Biology*, **16**, 1194-1212.

Bruinsma, J., 2009. The resource outlook to 2050: by how much do land, water and crop yields need to increase by 2050? In: *Proceedings of the Expert Meeting on How to Feed the World in 2050, 24-26 June 2009, FAO Headquarters, Rome*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 33 pp.

Bryan, E., T. Deressa, G. Gbetibouo, and C. Ringler, 2009: Adaptation to climate change in Ethiopia and South Africa: options and constraints. *Environmental Science and Policy*, **12**, 413-426.

Bunce, J.L., 2012: Responses of cotton and wheat photosynthesis and growth to cyclic variation in carbon dioxide concentration. *Photosynthetica*, **50**, 395-400.

Burke, L., K. Reytar, M. Spalding, and A. Perry, 2011: *Reefs at Risk Revisited. Executive Summary*. World Resources Institute, Washington, DC, USA, 10 pp.

Burke, M.B., D.B. Lobell, and L. Guarino, 2009: Shifts in African crop climates by 2050, and the implications for crop improvement and genetic resources conservation. *Global Environmental Change*, **19**, 317-325.

Butt, T.A., B.A. McCarl, J. Angerer, P.T. Dyke, and J.W. Stuth, 2005: The economic and food security implications of climate change in Mali. *Climatic Change*, **68(3)**, 355-378.

Byjesh, K.S., S. Naresh Kumar, and P.K. Aggarwal, 2010: Simulating impacts, potential adaptation and vulnerability of maize to climate change in India. *Mitigation and Adaptation Strategies for Global Change*, **15(5)**, 413-431.

Calzadilla, A., T. Zhu, K. Rehdanz, R.S.J. Tol, and C. Ringer, 2009: *Economywide Impacts of Climate Change on Agriculture in Sub-Saharan Africa*. International Food Policy Research Institute (IFPRI) Discussion Paper No. 873, IFPRI Environment and Production Technology Division, Washington, DC, USA, 35 pp.

Calzadilla, A., K. Rehdanz, R. Betts, P. Falloon, A. Wiltshire, and R.S.J. Tol, 2013: Climate change impacts on global agriculture. *Climatic Change*, **120(1-2)**, 357-374.

Campbell, A.A., S. de Pee, K. Sun, K. Kraemer, A. Thorne-Lyman, and R. Moench-Pfanner, 2010: Household rice expenditure and maternal and child nutritional status in Bangladesh. *Journal of Nutrition*, **140(Suppl. 1)**, 189S-194S.

Cannon, R.J.C., 1998: The implications of predicted climate change for insect pests in the UK, with emphasis on non-indigenous species. *Global Change Biology*, **4**, 785-796.

Cantarel, A.A.M., J.M.G. Bloor, and J.F. Soussana, 2013: Four years of simulated climate change reduces aboveground productivity and alters functional diversity in a grassland ecosystem. *Journal of Vegetation Science*, **24**, 113-126.

Carter, M.R. and T.J. Lybbert, 2012: Consumption versus asset smoothing: testing the implications of poverty trap theory in Burkina Faso. *Journal of Development Economics*, **99**, 255-264.

Ceccarelli, S., S. Grando, M. Maatougui, M. Michael, M. Slash, R. Haghparast, M. Rahmanian, A. Taheri, A. Al-Yassin, A. Benbelkacem, M. Labdi, H. Mimoun, and M. Nachit, 2010: Plant breeding and climate changes. *The Journal of Agricultural Science*, **148**, 627-637.

Chakraborty, S., J. Luck, A. Freeman, R.M. Norton, K.A. Garrett, K.E. Percy, A.A. Hopkin, C. Davis, and D.F. Karnosky, 2008: Impacts of global change on diseases of agricultural crops and forest types. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition, and Natural Resources*, **3**, No. 054,1-15.

Chakraborty, S. and A.C. Newton, 2011: Climate change, plant diseases and food security: an overview. *Plant Pathology*, **60**, 2-14.

Challinor, A.J. and T.R. Wheeler, 2008: Use of a crop model ensemble to quantify CO_2 stimulation of water-stressed and well-watered crops. *Agricultural and Forest Meteorology*, **148**, 1062-1077.

Challinor, A.J., T.R. Wheeler, D. Hemming, and H.D. Upadhyaya, 2009: Ensemble yield simulations: crop and climate uncertainties, sensitivity to temperature and genotypic adaptation to climate change. *Climate Research*, **38(2)**, 117-127.

Challinor, A.J., E.S. Simelton, E.G. Fraser, and D. Hemming, 2010: Increased crop failure due to climate change: assessing adaptation options using models and socio-economic data for wheat in China. *Environmental Research Letters*, **5(3)**, 034012.

Chen, C., E. Wang, Q. Yu, and Y. Zhang, 2010: Quantifying the effects of climate trends in the past 43 years (1961-2003) on crop growth and water demand in the North China Plain. *Climatic Change*, **100**, 559-578.

Chen, C., C. Lei, A. Deng, C. Qian, W. Hoogmoed, and W. Zhang, 2011: Will higher minimum temperatures increase corn production in Northeast China? An analysis of historical data over 1965-2008. *Agricultural and Forest Meteorology*, **151**, 1580-1588.

Cheung, W., V. Lam, J. Sarmiento, K. Kearney, R. Watson, D. Zeller, and D. Pauly, 2010: Large scale redistribution of maximum fisheries catch in the global ocean under climate change. *Global Change Biology*, **16(1)**, 24-35.

Cheung, W.L., R. Watson, and D. Pauly, 2013: Signature of ocean warming in global fisheries catch. *Nature*, **497**, 365-368.

Chhetri, N., W.E. Easterling, A. Terando, and L. Mearns, 2010: Modeling path dependence in agricultural adaptation to climate variability and change. *Annals of the Association of American Geographers*, **100(4)**, 894-907.

Chipanshi, A.C., R. Chanda, and O. Totolo, 2003: Vulnerability assessment of maize and sorghum crops to climate change in Botswana. *Climatic Change*, **61**, 339-360.

Cho, K., P. Falloon, J. Gornall, R. Betts, and Clark, 2012: Winter wheat yields in the UK: uncertainities in climate and management impacts. *Climate Research*, **54**, 49-68.

Christidis, N., P.A. Stott, S. Brown, G.C. Hegerl, and J. Caesar, 2005: Detection of changes in temperature extremes during the second half of the 20th century. *Geophysical Research Letters*, **32(20)**, L20716, doi:10.1029/2005GL023885.

Cinner, J.E., T.R. McClanahan, N.A.J. Graham, T.M. Daw, J. Maina, S.M. Stead, A. Wamukota, K. Brown, and Ö. Bodin, 2012: Vulnerability of coastal communities to key impacts of climate change on coral reef fisheries. *Global Environmental Change*, **22**, 12-20.

Ciscar, J., A. Iglesias, L. Feyen, L. Szabo, D. Regemorter, B. Amelung, R. Nicholls, P. Watkiss, O. Christensen, R. Dankers, L. Garrote, C. Goodess, A. Hunt, A. Moreno, J. Richards, and A. Soria, 2011: Physical and economic consequences of climate change in Europe. *Proceedings of the National Academy of Sciences of the United States of America*, **108**, 2678-2683.

Cochrane, K., W. Emerson, and R. Willmann, 2009: Sustainable fisheries: the importance of the bigger picture. In: *Sustainable Fisheries: Multi-Level Approaches to a Global Problem* [Taylor, W., A. Lynch, and M. Schechter (eds.)]. American Fisheries Society, Herndon, VA, USA, pp. 3-19.

Cochrane, K.L., N.L. Andrew, and A.M. Parma, 2011: Primary fisheries management: a minimum requirement for provision of sustainable human benefits in small-scale fisheries. *Fish and Fisheries*, **12**, 275-288.

Coles, A. and C. Scott, 2009: Vulnerability and adaptation to climate change and variability in semi-arid rural southeastern Arizona, USA. *Natural Resources Forum*, **33(4)**, 297-309.

Cook, R.M. and M.R. Heath, 2005: The implications of warming climate for the management of North Sea demersal fisheries. *ICES Journal of Marine Science*, **62**, 1322-1326.

Cooper, P., K.P.C. Rao, P. Singh, J. Dimes, P.S. Traore, K. Rao, P. Dixit, and S.J. Twomlow, 2009: Farming with current and future climate risk: advancing a "Hypothesis of Hope" for rainfed agriculture in semi-arid tropics. *Journal of Semi-Arid Tropics Agricultural Research*, **7**, 1-19.

Corobov, R., 2002: Estimations of climate change impacts on crop production in the Republic of Moldova. *GeoJournal*, **57(3)**, 195-202.

Costa, L.C., F. Justino, L.J.C. Oliveira, G.C. Sediyama, W.P.M. Ferreira, and C.F. Lemos, 2009: Potential forcing of CO_2, technology and climate changes in maize (*Zea mays*) and bean (*Phaseolus vulgaris*) yield in southeast Brazil. *Environmental Research Letters*, **4(1)**, 014013, doi:10.1088/1748-9326/4/1/014013.

Cotty, J.L. and R. Jaime-Garcia, 2007: Influences of climate on aflatoxin producing fungi and aflatoxin contamination. *International Journal of Food Microbiology*, **119**, 109-115.

Coulthard, S., 2008: Adapting to environmental change in artisanal fisheries – insights from a South Indian Lagoon. *Global Environmental Change*, **18(3)**, 479-489.

Cozzolino, D., W.U. Cynkar, R.G. Dambergs, M. Gishen, and P. Smith, 2010: Grape (*Vitis vinifera*) compositional data spanning ten successive vintages in the context of abiotic growing parameters. *Agriculture, Ecosystems & Environment*, **139**, 565-570.

Craine, J.M., A.J. Elmore, K.C. Olson, and D. Tolleson, 2010: Climate change and cattle nutritional stress. *Global Change Biology*, **16**, 2901-2911.

Craufurd, P.Q. and T.R. Wheeler, 2009: Climate change and the flowering time of annual crops. *Journal of Experimental Botany*, **60**, 2529-2539.

Craufurd, P.Q., V. Vadez, S.V.K. Jagadish, P.V.V. Prasad, and M. Zaman-Allah, 2013: Crop science experiments designed to inform crop modeling. *Agricultural and Forest Meteorology*, **170**, 8-18.

DaMatta, F.M., A. Grandis, B.C. Arenque, and M.S. Buckeridge, 2010: Impacts of climate changes on crop physiology and food quality. *Food Research International*, **43**, 1814-1823.

Daw, T., W. Adger, K. Brown, and M. Badjeck, 2009: Climate change and capture fisheries: potential impacts, adaptation and mitigation. In: *Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge* [Cochrane, K., C. De Young, D. Soto, and T. Bahri (eds.)]. Food and Agricultural Organization of the United Nations (FAO) Fisheries and Aquaculture Technical Paper No. 530, FAO, Rome, Italy, pp. 107-150.

De Bruin, K.C. and R. Dellink, 2011: How harmful are restrictions on adapting to climate change? *Global Environmental Change*, **21(1)**, 34-45.

DEFRA, 2006: *Food Security and the UK: An Evidence and Analysis Paper*. Department for Environment, Food, and Rural Affairs (DEFRA), Food Chain Analysis Group, London, UK, 87 pp.

De Jong, R., K.Y. Li, A. Bootsma, T. Huffman, G. Rohloff, and S. Gameda, 2001: *Crop Yield and Variability under Climate Change and Adaptive Crop Management Scenarios*. Final Report for Climate Change Action Fund Project A080, Eastern Cereal and Oilseed Research Centre (ECORC), Government of Canada Department of Agriculture and Agri-Food Canada, Ottowa, Ontario, Canada, 49 pp.

Deryng, D., W.J. Sacks, C.C. Barford, and N. Ramankutty, 2011: Simulating the effects of climate and agricultural management practices on global crop yield, *Global Biogeochemical Cycles*, **25**, GB2006, doi:10.1029/2009GB003765.

De Silva, S.S. and D. Soto, 2009: Climate change and aquaculture: potential impacts, adaptation and mitigation. In: *Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge* [Cochrane, K., C. De Young, D. Soto, and T. Bahri (eds.)]. Food and Agricultural Organization of the United Nations (FAO) Fisheries and Aquaculture Technical Paper 530, FAO, Rome, Italy, pp. 151-212.

Dell, M., B.F. Jones, and B.A. Olken, 2012: Temperature shocks and economic growth: evidence from the last half century. *American Economic Journal: Macroeconomics*, **4**, 66-95.

Dercon, S., 2004: Growth and shocks: evidence from rural Ethiopia. *Journal of Development Economics*, **74**, 309-329.

Dercon, S. 2006: Economic reform, growth and the poor. Evidence from rural Ethiopia. *Journal of Development Economics*, **81(1)**, 1-24.

Dercon, S. and L. Christiaensen, 2011: Consumption risk, technology adoption and poverty traps: evidence from Ethiopia. *Journal of Development Economics*, **96**, 159-173.

Deressa, T., R. Hassan, C. Ringler, T. Alemu, and M. Yesuf, 2009: Determinants of farmers' choice of adaptation methods to climate change in the Nile basin of Ethiopia. *Global Environmental Change*, **19**, 248-255.

Deryng, D., W.J. Sacks, C.C. Barford, and N. Ramankutty, 2011: Simulating the effects of climate and agricultural management practices on global crop yield. *Global Biogeochemical Cycles*, **25**, GB2006, doi:10.1029/2009GB003765.

Descheemaeker, K., T. Amede, and A. Haileslassie, 2010: Improving water productivity in mixed crop–livestock farming systems of sub-Saharan Africa. *Agricultural Water Management*, **97**, 579-586.

Dikmen, S. and P.J. Hansen, 2009: Is the temperature-humidity index the best indicator of heat stress in lactating dairy cows in a subtropical environment? *Journal of Dairy Science*, **92**, 109-116.

Dilling, L. and M.C. Lemos, 2011: Creating usable science: opportunities and constraints for climate knowledge use and their implications for science policy. *Global Environmental Change*, **21**, 680-689.

Dronin, N. and A. Kirilenko, 2011: Climate change, food stress, and security in Russia. *Regional Environmental Change*, **11(Suppl. 1)**, 167-178.

Droogers, P., 2004: Adaptation to climate change to enhance food security and preserve environmental quality: example for southern Sri Lanka. *Agricultural Water Management*, **66(1)**, 15-33.

Duchêne, E., F. Huard, V. Dumas, C. Schneider, and D. Merdinoglu, 2010: The challenge of adapting grapevine varieties to climate change. *Climate Research*, **41(3)**, 193-204.

Duval, B.D., P. Dijkstra, S.M. Natali, J.P. Megonigal, M.E. Ketterer, B.G. Drake, M.T. Lerdau, G. Gordon, A.D. Anbar, and B.A. Hungate, 2011: Plant-soil distribution of potentially toxic elements in response to elevated atmospheric CO_2. *Environmental Science and Technology*, **45**, 2570-2574.

Eastburn, D.M., A.J. McElrone, and D.D. Bilgin, 2011: Influence of atmospheric and climatic change on plant-pathogen interactions. *Plant Pathology*, **60**, 54-69.

Easterling, W.E., N. Chhetri, and X. Niu, 2003: Improving the realism of modeling agronomic adaptation to climate change: simulating technological substitution. *Climatic Change*, **60**, 149-173.

El-Maayar, M. and O. Sonnentag, 2009: Crop model validation and sensitivity to climate change scenarios. *Journal of Climate Research*, **39**, 47-59.

El-Shaher, H.M., C. Rosenzweig, A. Iglesias, M.H. Eid, and D. Hillel, 1997: Impact of climate change on possible scenarios for Egyptian agriculture in the future. *Mitigation and Adaptation Strategies for Global Change*, **1**, 233-250.

El-Sharkawy, M.A., 2012: Stress-tolerant cassava: the role of integrative ecophysiology-breeding research in crop improvement. *Open Journal of Soil Science*, **2(2)**, 162-186.

Emberson, L.D., P. Büker, M.R. Ashmore, G. Mills, L.S. Jackson, M. Agrawal, M.D. Atikuzzaman, S. Cinderby, M. Engardt, C. Jamir, K. Kobayashi, N.T.K. Oanh, Q.F. Quadir, and A. Wahid, 2009: A comparison of North American and Asian exposure-response data for ozone effects on crop yields. *Atmospheric Environment*, **43**, 1945-1953.

Erbs, M., R. Manderscheid, G. Jansen, S. Seddig, A. Pacholski, and H. Weigel, 2010: Effects of free-air CO_2 enrichment and nitrogen supply on grain quality parameters and elemental composition of wheat and barley grown in a crop rotation. *Agriculture, Ecosystem and Environment*, **136**, 59-68.

Erda, L., X. Wei, J. Hui, X. Yinlong, L. Yue, B. Liping, and X. Liyong, 2005: Climate change impacts on crop yield and quality with CO_2 fertilization in China. *Philosophical Transactions of the Royal Society B*, **360**, 2149-2154.

Ericksen, P., 2008: Conceptualizing food systems for global environmental change research. *Global Environmental Change*, **18**, 234-245.

Ericksen, P., B. Stewart, J. Dixon, D. Barling, P. Loring, M. Anderson, and J. Ingram, 2010: The value of a food system approach. In: *Food Security and Global Environmental Change* [Ingram, J., P. Ericksen, and D. Liverman (eds.)]. Earthscan, London, UK, pp. 25-45.

Ericksen, P., P. Thornton, A. Notenbaert, L. Cramer, P. Jones, and M. Herero, 2011: *Mapping Hotspots of Climate Change and Food Insecurity in the Global Tropics.* CCAFS Report No. 5, CGIAR Research Program on Climate Change, Agriculture, and Food Security (CCAFS), Copenhagen, Denmark, 56 pp.

Evans, N., A. Baierl, M.A. Semenov, P. Gladders, and B.D.L. Fitt, 2008: Range and severity of a plant disease increased by global warming. *Journal of the Royal Society Interface*, **5**, 525-531.

Ewert, F., M.D.A. Rounsevell, I. Reginster, M.J. Metzger, and R. Leemans, 2005: Future scenarios of European agricultural land use: I. Estimating changes in crop productivity. *Agriculture Ecosystems & Environment*, **107(2-3)**, 101-116.

Fafchamps, M., 1992: Solidarity networks in pre-industrial societies: rational peasants with a moral economy. *Economic Development and Cultural Change*, **41**, 147-174.

Fafchamps, M., 1999: *Rural Poverty, Risk and Development*. Economic and Social Development Paper, No. 144, Food and Agricultural Organization of the United Nations (FAO), Rome, Italy, 131 pp.

Fafchamps, M., 2009: *Vulnerability, Risk Management, and Agricultural Development*. Center for Effective Global Action (CEGA) Working Paper No. AfD-0904, CEGA AfD Working Paper Series containing papers presented at the "Agriculture for Development in Sub-Saharan Africa Conference," May 28-30, 2009, Mombasa, Kenya, sponsored by CEGA and the African Economic Research Consortium (AERC), CEGA, University of California, Berkeley, Berkeley, CA, USA, 29 pp.

Falloon, B. and R. Betts, 2010: Climate impacts on European agriculture and water management in the context of adaptation and mitigation – the importance of an integrated approach. *Science of the Total Environment*, **408**, 5667-5687.

FAO, 1996: *Rome Declaration and World Food Summit Plan of Action*. Food and Agricultural Organization of the United Nations (FAO) World Food Summit, Rome, Italy, 13-17 November 1996, FAO, Rome, Italy, www.fao.org/docrep/003/w3613e/w3613e00.HTM.

FAO, 2008: *The State of Food Insecurity in the World: High Food Prices and Food Security—Threats and Opportunities*. Food and Agricultural Organization of the United Nations (FAO), Rome, Italy, 56 pp.

FAO, 2009a: Introduction. In: *Climate Change Implications or Fisheries and Aquaculture: Overview of Current Scientific Knowledge* [Cochrane, K., C. De Young, D. Soto, and T. Bahri (eds.)]. Food and Agricultural Organization of the United Nations (FAO) Fisheries and Aquaculture Technical Paper 530, FAO, Rome, Italy, pp. 1-5.

FAO, 2009b: *The State of Agricultural Commodity Markets 2009: High Food Prices and the Food Crisis –Experiences and Lessons Learned.* Food and Agricultural Organization of the United Nations (FAO), Rome, Italy, 63 pp.

FAO, 2010: *The State of Food Insecurity in the World: Addressing Food Insecurity in Protracted Crises*. Food and Agricultural Organization of the United Nations (FAO), Rome, Italy, 50 pp.

FAO, 2011: The *State of Food Insecurity in the World: How does International Price Volatility affect Domestic Economies and Food?* Food and Agricultural Organization of the United Nations (FAO), Rome, Italy, 52 pp.

FAO, 2012: *The State of World Fisheries and Aquaculture 2012*. Food and Agricultural Organization of the United Nations (FAO), Rome, Italy, 209 pp.

FAO, WFP, and IFAD, 2012: *The State of Food Insecurity in the World: Economic Growth is Necessary but not Sufficient to Accelerate Reduction of Hunger and Malnutrition*. Food and Agricultural Organization of the United Nations (FAO), the International Fund for Agricultural Development (IFAD), and the World Food Programme (WFP), FAO, Rome, Italy, 62 pp.

Farag, A.A., A.A. Khalil, and M.K. Hassanein, 2010: Chilling requirement for deciduous fruit under climate change in Egypt. *Research Journal of Agriculture and Biological Sciences*, **6**, 815-822.

Fatondji, D., C. Martius, R. Zougmore, P. Vlek, C. Bielders, and S. Koala, 2009: Decomposition of organic amendment and nutrient release under the Zai technique in the Sahel. *Nutrient Cycling in Agroecosystems*, **85**, 225-239.

Feder, G., R. Just, and D. Zilberman, 1985: Adoption of agricultural innovations in developing countries: a survey. *Economic Development and Cultural Change*, **33**, 255-298.

Feng, J., M. Zhang, S. Zheng, P. Xie, and A. Ma, 2008a: Effects of high temperature on multiple parameters of broilers in vitro and in vivo. *Poultry Science*, **87**, 2133-2139.

Feng, Z., K. Koyabashi, and E.A. Ainsworth, 2008b: Impact of elevated ozone concentration on growth, physiology and yield of wheat (*Triticum aestivum* L.): a meta analysis. *Global Change Biology*, **14**, 2696-2708.

Feng, Z., J. Pang, K. Kobayashi, J. Zhu, and D.R. Ort, 2011: Differential responses in two varieties of winter wheat to elevated ozone concentration under fully open-air field conditions. *Global Change Biology*, **17**, 580-591.

Fernando, N., J. Panozzo, M. Tausz, R. Norton, G. Fitzgerald, and S. Seneweera, 2012: Rising atmospheric CO_2 concentration affects mineral content and protein concentration of wheat grain. *Food Chemistry*, **133**, 1307-1311.

Ficke, A.D., C.A. Myrick, and L.J. Hansen, 2007: Potential impacts of global climate change on freshwater fisheries. *Review in Fish Biology and Fisheries*, **17**, 581-613.

Fischer, G., E. Hizsnyik, S. Prieler, M. Shah, and H. van Velthuizen, 2009: *Biofuels and Food Security*. Report by the International Institute for Applied Systems Analysis (IIASA) for the OPEC Fund for International Development (OFID), OFID, Vienna, Austria, 223 pp.

Fishman, J., J.K. Creilson, P.A. Parker, E.A. Ainsworth, G.G. Vining, J. Szarka, F.L. Booker, and X. Xu, 2010: An Investigation of widespread ozone damage to the soybean crop in the upper Midwest determined from ground-based and satellite measurements. *Atmospheric Environment*, **44**, 2248-2256.

Fitzgerald, J., A. Brereton, and N. Holden, 2008: Assessment of the adaptation potential of grass-based dairy systems to climate change in Ireland – the maximised production scenario. *Agricultural and Forest Meteorology*, **149(2)**, 244-255.

Fleisher, D.H., D.J. Timlin, and V.R. Reddy, 2008: Interactive effects of carbon dioxide and water stress on potato canopy growth and development. *Agronomy Journal*, **100**, 711-719.

Ford, D., 2009: Vulnerability of Inuit food systems to food insecurity as a consequence of climate change: a case study from Igloolik, Nunavut. *Regional Environmental Change*, **9**, 83-100.

Fraser, E., M. Termansen, N. Sun, D. Guan, E. Simelton, P. Dodds, K. Feng, and Y. Yu, 2008: Quantifying socioeconomic characteristics of drought-sensitive regions: evidence from Chinese provincial agricultural data. *Comptes Rendus Geoscience*, **340(9-10)**, 679-688.

Fuhrer, J., 2009: Ozone risk for crops and pastures in present and future climates. *Naturwissenschaften*, **96**, 173-194.

Fujisawa, M. and K. Koyabashi, 2010: Apple (*Malus pumila var. domestica*) phenology is advancing due to rising air temperature in northern Japan. *Global Change Biology*, **16(10)**, 2651-2660.

Fulton, E.A., 2011: Interesting times: winners, losers, and system shifts under climate change around Australia. *ICES Journal of Marine Science*, **68**, 1329-1342.

García-Mozo, H., A. Mestre, and C. Galán, 2010: Phenological trends in southern Spain: a response to climate change. *Agricultural and Forest Meteorology*, **150**, 575-580.

Garrett, K.A., G.A. Forbes, S. Savary, P. Skelsey, A.H. Sparks, C. Valdivia, A.H.C. van Bruggen, L. Willocquet, A. Djurle, E. Duveiller, H. Eckersten, S. Pande, C. Vera Cruz, and J. Yuen, 2011: Complexity in climate-change impacts: an analytical framework for effects mediated by plant disease. *Plant Pathology*, **60(1)**, 15-30.

Gaughan, J.B., S. Bonner, I. Lozxton, T.L. Mader, A. Lisle and R. Lawrence, 2010: Effect of shade on body temperature and performance of feedlot steers. *Journal of Animal Science*, **88(12)**, 4056-4067.

Gbetibouo, G.A. and R.M. Hassan, 2005: Measuring the economic impact of climate change on major South African field crops: a Ricardian approach. *Global and Planetary Change*, **47(2-4)**, 143-152.

Ghahramani, A. and A. Moore, 2013: Climate change and broadacre livestock production across southern Australia. 2. Adaptation options via grassland management. *Crop and Pasture Science*, **64(6)**, 615-630.

Ghini, R., E. Hamada, M.J. Pedro, J.A. Marengo, and R.R.V. Gonçalves, 2008: Risk analysis of climate change on coffee nematodes and leaf miner in Brazil. *Pesquisa Agropecuária Brasileira*, **43**, 187-195.

Ghorbanian, D., S. Harutyunyan, D. Mazaheri, and F. Rejali, 2011: Effects of mycorrhizal symbiosis and different levels of phosphorus on yield, macro and micro elements of *Zea mays* L. under water stress condition. *Journal of Agricultural Research*, **6**, 5481-5489.

Giannakopoulos, C., P. Le Seger, M. Bindi, M. Moriondo, E. Kostopoulou, and C. Goodess, 2009: Climatic changes and associated impacts in the Mediterranean resulting from a 2 °C global warming. *Global and Planetary Change*, **68**, 209-224.

Gilbert, M., J. Slingenbergh, and X. Xiao, 2008: Climate change and avian influenza. *Revue Scientifique et Technique (Office International des Epizooties)*, **27**, 459-466.

Gillespie, K.M., F. Xu, K.T. Richter, J.M. McGrath, R.J.C. Markelz, D.R. Ort, and A.D.B. Leakey, 2012: Greater anti-oxidant and respiratory metabolism in field grown soybean exposed to elevated O_3 under both ambient and elevated CO_2. *Plant, Cell & Environment*, **35**, 169-184.

Gleadow, R.M., J.R. Evans, S. McCaffrey, and T.R. Cavagnara, 2009: Growth and nutritive value of cassava (*Manihot esculenta Cranz*.) are reduced when grown in elevated CO_2. *Plant Biology*, **11**, 76-82.

Glenn, M., S.Y. Kim, J. Ramirez-Villegas, and P. Laderach, 2013: Chapter 2: Response of perennial horticultural crops to climate change. In: *Horticultural Reviews* [Janick, J. (ed.)]. Vol. 41, Wiley-Blackwell, Hoboken, NJ, USA, pp. 47-130.

Goklany, I.M., 2007: Integrated strategies to reduce vulnerability and advance adaptation, mitigation and sustainable development. *Mitigation and Adaptation Strategies for Global Change*, **12**, 755-786.

Goodman-Elgar, M., 2008: Evaluating soil resilience in long-term cultivation: a study of pre-Columbian terraces from the Paca Valley, Peru. *Journal of Archaeological Science*, **35(12)**, 3072-3086.

Goswami, S.B., S. Matin, S. Aruna, and G.D. Bairagi, 2012: A review: the application of remote sensing, GIS and GPS in precision agriculture. *Journal of Advanced Technology and Engineering Research*, **2**, 50-54.

Grab, S. and A. Craparo, 2011: Advance of apple and pear tree full bloom dates in response to climate change in the southwestern Cape, South Africa: 1973-2009. *Agricultural and Forest Meteorology*, **151**, 406-413.

Grafton, R.Q., 2010: Adaptation to climate change in marine capture fisheries. *Marine Policy*, **34**, 606- 615.

Graux, A.-I., M. Gaurut, J. Agabriel R. Baumont, R. Delagarde, L. Delaby, and J.-F. Soussana, 2011: Development of the Pasture Simulation Model for assessing livestock production under climate change. *Agriculture, Ecosystems and Environment*, **144**, 69-91.

Graux, A.-I., G. Bellocchi, R. Lardy, and J. Soussana, 2013: Ensemble modelling of climate change risks and opportunities for managed grasslands in France. *Agricultural and Forest Meteorology*, **170**, 114-131.

Green, D., J. Billy, A. Tapim, 2010: Indigenous Australians' knowledge of weather and climate. *Climate Change*, **100**, 337-354.

Gregory, P. J., S. N. Johnson, A. C. Newton and J. S. I. Ingram, 2009: Integrating pests and pathogens into the climate change/food security debate. *Journal of Experimental Botany*, **60 (10)**, 2827-2838.

Gregory, P.J. and B.E. Marshall, 2012: Attribution of climate change: a methodology to estimate the potential contribution to increases in potato yield in Scotland since 1960. *Global Change Biology*, **18**, 1372-1388.

Guis, H., C. Caminade, C. Calvete, A.P. Morse, A. Tran, and B. Baylis, 2012: Modelling the effects of past and future climate on the risk of bluetongue emergence in Europe. *Journal of the Royal Society Interface*, **9**, 339-350.

Gummow, B., 2010: Challenges posed by new and re-emerging infectious diseases in livestock production, wildlife and humans. *Livestock Science*, **130**, 41-46.

Hall, A. and G.V. Jones, 2009: Effect of potential atmospheric warming on temperature-based indices describing Australian winegrape growing conditions. *Australian Journal of Grape and Wine Research*, **15**, 97-119.

Hannukkala, A.O., T. Kaukoranta, A. Lehtinen, and A. Rahkonen, 2007: Late-blight epidemics on potato in Finland, 1933-2002; increased and earlier occurrence of epidemics associated with climate change and lack of rotation. *Plant Pathology*, **56**, 167-176.

Hanslow, K., D. Gunesekera, B.R. Cullen, and D. Newth, 2014: Economic impacts of climate change on the Australian dairy sector. *Australian Journal of Agricultural and Resource Economics*, **58**, 60-77.

Hasegawa, T., H. Sakai, T. Tokida, H. Nakamura, C. Zhu, Y. Usui, M. Yoshimoto, M. Fukuoka, H. Wakatsuki, N. Katayanagi, T. Matsunami, Y. Kaneta, T. Sato, F. Takakai, R. Sameshima, M. Okada, T. Mae, and A. Makino, 2013: Rice cultivar responses to elevated CO_2 at two free-air CO_2 enrichment (FACE) sites in Japan. *Functional Plant Biology*, **40**, 148-159.

Hatfield, J.L., K.J. Boote, B.A. Kimball, L.H. Ziska, R.C. Izaurralde, D. Ort, A.M. Thomson, and D. Wolfe, 2011: Climate impacts on agriculture: implications for crop production. *Agronomy Journal*, **103(2)**, 351-370.

Hawkins, E., T.M. Osborne, C.K. Hoa, and A.C. Challinor, 2012: Calibration and bias correction of climate projections for crop modelling: an idealised case study over Europe. *Agricultural and Forest Meteorology*, **170**, 19-31.

Hayes, F., G. Mills, H. Harmens, and D. Norris, 2007: *Evidence of Widespread Ozone Damage to Vegetation in Europe (1990-2006)*. Centre for Ecology and Hydrology, Natural Environment Research Council, Bangor, Wales, UK, pp. 1-58.

Headey, D. and S. Fan, 2010: *Reflections on the Global Food Crisis: How Did It Happen? How Has It Hurt? And How Can We Prevent The Next One?* International Food Policy Research Institute (IFPRI), Washington DC, USA, 122 pp.

Hellmann, J.J., J.E. Byers, B.G. Bierwagen, and J.S. Dukes, 2008: Five potential consequences of climate change for invasive species. *Conservation Biology*, **22**, 534-543.

Heltberg, R. and F. Tarp, 2002: Agricultural supply response and poverty in Mozambique. *Food Policy*, **27(2)**, 103-124.

Hermans, C., I. Geijzendorffer, F. Ewert, M. Metzger, P. Vereijken, G. Woltjer, and A. Verhgen, 2010: Exploring the future of European crop production in a liberalized market, with specific consideration of climate and the regional competitiveness. *Ecological Modeling*, **221**, 2177-2187.

Hertel, T.W., M.B. Burke, and D.B. Lobell, 2010: The poverty implications of climate-induced crop yield changes by 2030. *Global Environmental Change*, **20**, 577-585.

HLPE, 2011: *Price Volatility and Food Security*. A Report by the High Level Panel of Experts (HLPE) on Food Security and Nutrition of the Committee on World Food Security, HLPE, Rome, Italy, 79 pp.

Hoddinot, J., J. Maluccio, J.R. Behrman, R. Flores, and R. Martorell, 2008: Effect of a nutrition intervention during early childhood on economic productivity in Guatemalan adults. *The Lancet*, **371**, 411-416.

Hoegh-Guldberg, O., 2011: Coral reef ecosystems and anthropogenic climate change. *Regional Environmental Change*, **11**, 215-227.

Hoegh-Guldberg, O., P.J. Mumby, A.J. Hooten, R.S. Steneck, P. Greenfield, E. Gomez, C.D. Harvell, P.F. Sale, A.J. Edwards, K. Caldeira, N. Knowlton, C.M. Eakin, R. Iglesias-Prieto, N. Muthiga, R.H. Bradbury, A. Dubi, and M.E. Hatziolos, 2007: Coral reefs under rapid climate change and ocean acidification. *Science*, **318**, 1737-1742.

Hoffmann, I., 2010: Climate change and the characterization, breeding and conservation of animal genetic resources. *Animal Genetics*, **41**, 32-46.

Högy, P. and A. Fangmeier, 2009: Atmospheric CO_2 enrichment affects potatoes: 1. Above-ground biomass production and tuber yield. *European Journal of Agronomy*, **30**, 78-84.

Högy, P., H. Wiesier, P. Kohler, K. Schwadorf, J. Breuer, J. Franzaring, R. Muntifering, and A. Fangmeier, 2009: Effects of elevated CO_2 on grain yield and quality of wheat: results from a 3-year free-air CO_2 enrichment experiment. *Plant Biology*, **11(Suppl. 1)**, 60-69.

Hollaway, M.J., S.R. Arnold, A.J. Challinor, and L.D. Emberson, 2011: Intercontinental trans-boundary contribution to ozone-induced crop yield losses in Northern Hemisphere. *Biogeosciences Discussion*, **8**, 8645-8691.

Howden, M. and R.N. Jones, 2004: Risk assessment of climate change impacts on Australia's wheat industry. In: *New Directions for a Diverse Planet: Proceedings of the 4th International Crop Science Congress, 26 September – 1 October 2004, Brisbane, Australia* [Fischer, T., N. Turner, J. Angus, L. McIntyre, M. Robertson, A. Borrell, and D. Lloyd (eds.)]. The Regional Institute Ltd., Gosford, Australia, www.cropscience.org.au/icsc2004/symposia/6/2/1848_howdensm.htm.

Howden, M., S.J. Crimp, and C.J. Stokes, 2008: Climate change and Australian livestock systems: impacts, research and policy issues. *Australian Journal of Experimental Agriculture*, **48**, 780-788.

Howden, M., S. Crimp, and R. Nelson, 2010: Australian agriculture in a climate of change. In: *Managing Climate Change: Papers from the GREENHOUSE 2009 Conference* [Jubb, I., P. Holper, and W. Cai (eds.)]. Commonwealth Scientific and Industrial Research Organization (CSIRO) Publishing, Collingwood, Australia, pp. 101-111.

Hsiang, S.M., 2010: Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America. *Proceedings of the National Academy of Sciences of the United States of America*, **107(35)**, 15367-15372.

Hsiang, S.M., K.C. Meng, and M.A. Cane, 2011: Civil conflicts are associated with the global climate. *Nature*, **476**, 438-441.

Huppert, D.D., A. Moore, and K. Dyson, 2009: Impacts of climate change on the coasts of Washington State. In: *Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate* (Elsner, M.M., J. Littel, and L. Whitely Binder (eds.)]. Climate Impacts Group, University of Washington, Seattle, WA, USA, 285-310.

Hurley, T., 2010: *Review of Agricultural Production Risk in the Developing World*. HarvestChoice Working Paper 11, International Food Policy Research Institute (IFPRI), Washington, DC, USA, 56 pp.

IAASTD, 2009: *Synthesis Report: A Synthesis of the Global and Sub-Global IAASTD Reports.* International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD), Island Press, Washington, DC, USA, 95 pp., www.unep.org/dewa/agassessment/reports/IAASTD/EN/Agriculture%20at%20a%20Crossroads_Synthesis%20Report%20(English).pdf.

IFAD, 2010: *The Rural Poverty Report 2011: New Realities, New Challenges: New Opportunities for Tomorrow's Generation*. International Fund for Agricultural Development (IFAD), Rome, Italy, 317 pp.

Iglesias, A., C. Rosenzweig, and D. Pereira, 2000: Agricultural impacts of climate change in Spain: developing tools for a spatial analysis. *Global Environmental Change*, **10**, 69-80.

Iglesias, A., L. Garrote, S. Quiroga, and M. Moneo, 2012: A regional comparison of the effects of climate change on agricultural crops in Europe. *Climatic Change*, **112(1)**, 29-46.

Iizumi, T., M. Yokozawa, and M. Nishimori, 2009: Parameter estimation and uncertainty analysis of a large-scale crop model for paddy rice: application of a Bayesian approach. *Agricultural and Forest Meteorology*, **149**, 333-348.

Iizumi, T., M. Yokozawa, and M. Nishimori, 2011: Probabilistic evaluation of climate change impacts on paddy rice productivity in Japan. *Climatic Change*, **107**, 391-415.

Ingram, J., 2011: A food systems approach to researching interactions between food security and global environmental change. *Food Security*, **3(4)**, 417-431.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp.

Iqbal, M.A., J. Eitzinger, H. Formayer, A. Hassan, and L.K. Heng, 2011: A simulation study for assessing yield optimization and potential for water reduction for summer-sown maize under different climate change scenarios. *Journal of Agricultural Science*, **149**, 129-143.

Iqbal, M.M., M.A. Goheer, and A.M. Khan, 2009: Climate-change aspersions on food security of Pakistan. *Science Vision*, **15(1)**, 15-23.

Ivanic, M. and W. Martin, 2008: Implications of higher global food prices for poverty in low-income countries. *Agricultural Economics*, **39**, 405-416.

Ivanic, M., W. Martin, and H. Zaman, 2011: *Estimating the Short-Run Poverty Impacts of the 2010-11 Surge in Food Price*. Policy Research Working Paper 5633, The World Bank, Washington, DC, USA, 33 pp.

Izaurralde, R., D. Adams, R. Alig, C. Betz, C. Hutchins, B. McCarl, K. Skog, and B. Sohngen, 2001: Assessing socioeconomic impacts of climate change on US forests, wood-product markets, and forest recreation. *BioScience*, **51**, 753-764.

Izaurralde, R.C., A.M. Thomson, N.J. Rosenberg, and R.A. Brown, 2005: Climate change impacts for the conterminous USA: an integrated assessment. Part 6. Distribution and productivity of unmanaged ecosystems. *Climatic Change*, **69**, 107-126.

Izaurralde, R.C., A.M. Thomson, J.A. Morgan, P.B. Fay, H.W. Polley, and J.L. Hatfield, 2011: Climate impacts on agriculture: implications for forage and rangeland production. *Agronomy Journal*, **103(2)**, 371-381.

Jadadish, K., P.Q. Craufurd, and T.R. Wheeler, 2007: High temperature stress and spikelet fertility in rice (*Oryza Sativa* L.). *Journal of Experimental Biology*, **58**, 1627-1635.

Jaggard, K., A. Qi, and M.A. Semenov, 2007: The impact of climate change on sugarbeet yield in the UK: 1976-2004. *The Journal of Agricultural Science*, **145**, 367-375.

Jarvis, A., J. Ramirez-Villegas, B. Herrera Campo, and C. Navarro-Racines, 2012: Is cassava the answer to African climate change adaptation? *Tropical Plant Biology*, **51**, 9-29.

Jones, P.G. and P.K. Thornton, 2003. The potential impacts of climate change on maize production in Africa and Latin America in 2055. *Global Environmental Change*, **13(1),** 51-59.

Jones, P.G. and P.K. Thornton, 2009: Croppers to livestock keepers: livelihood transitions to 2050 in Africa due to climate change. *Environmental Science & Policy*, **12**, 427-437.

Jones, G.V., M.A. White, O.R. Cooper, and K. Storchmann, 2005: Climate change and global wine quality. *Climatic Change*, **73(3)**, 319-343.

Jones, G.V., A.A. Duff, A. Hall, and J.W. Myers, 2010: Spatial analysis of climate in wine-grape growing regions in the western United States. *American Journal of Enology and Viticulture*, **61(3)**, 313-326.

Jorquera-Fontena, E. and R. Orrego-Verdugo, 2010: Impact of global warming on the phenology of a variety of grapevine grown in southern Chile. *Agrociencia*, **44(4)**, 427-435.

Joshi, M., R. Sutton, J. Lowe, and D. Frame, 2011: Projections of when temperature change will exceed 2 °C above pre-industrial levels. *Nature Climate Change*, **1**, 407-412.

Kabubo-Mariara, J., 2008: Climate change adaptation and livestock activity choices in Kenya: an economic analysis. *Natural Resources Forum*, **32**, 131-141.

Kabubo-Mariara, J., 2009: Global warming and livestock husbandry in Kenya: impacts and adaptations. *Ecological Economics*, **68(7)**, 1915-1924.

Kalanda-Joshua, M., C. Ngongondo, L. Chipeta, and F. Mpembeka, 2011: Integrating indigenous knowledge with conventional science: enhancing localised climate and weather forecasts in Nessa, Mulanje, Malawi. *Physics and Chemistry of the Earth*, **36(14)**, 996-1003.

Kaiser, H.M., 1999: Assessing research on the impacts of climate change on agriculture. In: *Global Environmental Change and Agriculture: Assessing the Impacts* [Frisvold, G. and B. Kuhn (eds.)]. Edward Elgar Publishing, Cheltenham, UK, pp. 221-238.

Kang, Y., S. Khan, and X. Ma, 2009: Climate change impacts on crop yield, crop water productivity and food security – a review. *Progress in Natural Science*, **19**, 1665-1674.

Kapetanaki, G. and C. Rosenzweig, 1997: Impact of climate change on maize yield in central and northern Greece: a simulation study with Ceres-Maize. *Mitigation and Adaptation Strategies for Global Change*, **1(3)**, 251-271.

Karfakis, P., M. Knowles, M. Smulders, and J. Capaldo, 2011: *Effects of Global Warming on Vulnerability to Food Insecurity in Rural Nicaragua*. ESA Working Paper No. 11-18, Agricultural Development Economics Division (ESA), Food and Agricultural Organization of the United Nations (FAO), Rome, Italy, 33 pp.

Karim, Z., S.G. Hussain, and M. Ahmed, 1996: Assessing impacts of climatic variations on food grain production in Bangladesh. In: *Climate Change Vulnerability and Adaptation in Asia and the Pacific* [Erda, L., W.C. Bolhofer, S. Huq, S. Lenhart, S.K. Mukherjee, J.B. Smith, and J. Wisniewski (eds.)]. Regional Workshop, 15-19 January 1996, Manila, Philippines, Reprinted from Water, Air, and Soil Pollution, 92(1-2), 1996 edition, Springer, Dordrecht, Netherlands, pp. 53-62.

Kassie, M., J. Pender, Y. Mahmud, G. Kohlin, R. Bluffstone, and E. Mulugeta, 2008: Estimating returns to soil conservation adoption in the Northern Ethiopian Highlands. *Agricultural Economics*, **38**, 213-232.

Kates, R., W. Travis, and T. Wilbanks, 2012: Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences of the United States of America*, **109**, 7156-7161.

Kazianga, H. and C. Udry, 2006: Consumption smoothing? Livestock, insurance and drought in rural Burkina Faso. *Journal of Development Economics*, **79**, 413-446.

Kearney, J., 2010: Food consumption trends and drivers. *Philosophical Transactions of the Royal Society B*, **365**, 2793-2807.

Kim, C., S. Lee, H. Jeong, J. Jang, Y. Kim, and C.Lee, 2010: *Impacts of Climate Change on Korean Agriculture and its Counterstrategies*. Korea Rural Economic Institute, Seoul, South Korea, 282 pp.

Kimball, B.A., 2010: Lessons from FACE: CO_2 effects and interactions with water, nitrogen and temperature. In: *Handbook of Climate Change and Agroecosystems: Impacts, Adaptation and Mitigation* [Hillel, D. and C. Rozenweig (eds.)]. Imperial College Press, London, UK, pp. 87-107.

Kirsch, T., C. Wadhwani, L. Sauer, S. Doocy, and C. Catlett, 2012: Impact of the 2010 Pakistan floods on rural and urban populations at six months. *PLoS Currents Disasters*, August 22, Edition 1, doi:10.1371/4fdfb212d2432.

Kiselev, S., R. Romashkin, G. Nelson, D. Mason-D'Croz, and A. Plazzo, 2013: *Russia's Food Security and Climate Change: Looking into the Future*. Economics Discussion Papers, No. 2013-16, Kiel Institute for the World Economy, Kiel, Germany, 58 pp.

Knox, J., T. Hess, A. Daccache, and T. Wheeler, 2012: Climate change impacts on crop productivity in Africa and South Asia. *Environmental Research Letters*, **7**, 034032, doi:10.1088/1748-9326/7/3/034032.

Koehler, A., A. J. Challinor, E. Hawkins, and S. Asseng, 2013: Influences of increasing temperature on Indian wheat: quantifying limits to predictability. *Environmental Research Letters*, **8**, 034016, doi:10.1088/1748-9326/8/3/034016.

Koehn, J.D., A.J. Hobday, M.S. Pratchett, and B.M. Gillanders, 2011: Climate change and Australian marine and freshwater environments, fishes and fisheries: synthesis and options for adaptation. *Marine and Freshwater Research*, **62(9)**, 1148-1164.

Krishnan, P., D. Swain, B. Bhaskar, S. Nayak, and R. Dash, 2007: Impact of elevated CO_2 and temperature on rice yield and methods of adaptation as evaluated by crop simulation studies. *Agricultural Ecosystems and Environment*, **122**, 233-242.

Kucharik, C.J. and S.P. Serbin, 2008: Impacts of recent climate change on Wisconsin corn and soybean yield trends. *Environmental Research Letters*, **3**, 034003, doi:10.1088/1748-9326/3/3/034003.

Kulshreshtha, S.N., 2011: Climate change, prairie agriculture, and prairie economy: the new normal. *Canadian Journal of Agricultural Economics*, **59(1)**, 19-44.

Kumar, S.N., P.K. Aggarwal, S. Rani, S. Jain, R. Saxena, and N. Chauhan, 2011: Impact of climate change on crop productivity in Western Ghats, coastal and northeastern regions of India. *Current Science*, **101(3)**, 332-341.

Kumar, S.N., P.K. Aggarwal, R. Saxena, S. Rani, S. Jain, and N. Chauhan, 2013: An assessment of regional vulnerability of rice to climate change in India. *Climatic Change*, **118(3-4)**, 683-699.

Kvalvik, I., S. Dalmannsdottir, H. Dannevig, G. Hovelsrud, L. Rønning, and E. Uleberg, 2011: Climate change vulnerability and adaptive capacity in the agricultural sector in Northern Norway. *Acta Agriculturae Scandinavica*, *Section B – Soil & Plant Science*, **61(S1)**, 27-37.

Lal, M., 2011: Implications of climate change in sustained agricultural productivity in South Asia. *Regional Environmental Change*, **11(Suppl. 1)**, S79-S94.

Lal, M., K.K. Singh, L.S. Rathore, G. Srinivasan, and S.A. Saseendran, 1998: Vulnerability of rice and wheat yields in NW India to future changes in climate. *Agricultural and Forest Meteorology*, **89(2)**, 101-114.

Lancelot, R., S. de La Rocque, and V. Chevalier, 2008: Bluetongue and Rift Valley fever in livestock: a climate change perspective with a special reference to Europe, the Middle East and Africa. In: *Livestock and Global Climate Change: Proceedings of the British Society of Animal Science (BSAS) International Conference on Livestock and Global Climate Change in Hammamet, Tunisia, 17-20 May 2008* [Rowlinson, P., M. Steele, and A. Nefzaoui (eds.)]. Cambridge University Press, Cambridge, UK, pp. 87-89.

Lanning, S.B., T.J. Siebenmorgen, P.A. Counce, A.A. Ambardekar, and A. Mauromoustakos, 2011: Extreme nighttime air temperatures in 2010 impact rice chalkiness and milling quality. *Field Crops Research*, **124**, 132-136.

Last, P., W. White, D. Gledhill, A. Hobday, R. Brown, G. Edgar, and G. Pecl, 2011: Long term shifts in abundance and distribution of a temperate fish fauna: a response to climate change and fishing practices. *Global Ecology and Biogeography*, **20**, 58-72.

Laux, P., G. Jacket, R. Tingem, and H. Kunstmann, 2010: Impact of climate change on agricultural productivity under rainfed conditions in Cameroon – a method to improve attainable crop yields by planting date adaptations. *Agricultural and Forest Meteorology*, **150**, 1258-1271.

Leakey, A.D.B., 2009: Rising atmospheric carbon dioxide concentration and the future of C_4 crops for food and fuel. *Proceedings of the Royal Society B*, **276(1666)**, 2333-2343.

Lehodey, P., J. Hampton, R.W. Brill, S. Nicol, I. Senina, B. Calmettes, H. Portner, L. Bopp, T. Llyina, J.D. Bell, and J. Sibert, 2011: Vulnerability of oceanic fisheries in the tropical Pacific to climate change. In: *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change* [Bell, J.D., J.E. Johnson, and A.J. Hobday (eds.)]. Secretariat of the Pacific Community, Noumea, New Caledonia, pp. 433-492.

Lemos, M.C. and R.B. Rood, 2010: Climate projections and their impact on policy and practice. *Wiley Interdisciplinary Reviews: Climate Change*, **1**, 13.

Lenz-Wiedemann, V.I.S., C.W. Klar, and K. Schneider, 2010: Development and test of a crop growth model for application within a global change decision support system. *Ecological Modelling*, **221**, 314-329.

Li, S., T. Wheeler, A. Challinor, E. Lin, H. Ju, and Y. Xu, 2010: The observed relationships between wheat and climate in China. *Agricultural and Forest Meteorology*, **150**, 1412-1419.

Li, X., T. Takahashi, S. Nobuhiro, and H.M. Kaiser, 2011: The impact of climate change on maize yields in the United States and China. *Agricultural Systems*, **104(4)**, 348-353.

Licker, R., C.J. Kucharik, T. Doré, M.J. Lindeman, and D. Makowski, 2013: Climatic impacts on winter wheat yields in Picardy, France and Rostov, Russia: 1973-2010. *Agricultural and Forest Meteorology*, **176**, 25-37.

Lioubimtseva, E. and G.M. Henebry, 2009: Climate and environmental change in arid Central Asia: impacts, vulnerability and adaptations. *Journal of Arid Environments*, **73(11)**, 963-977.

Liu, S., X. Mo, Z. Lin, Y. Xu, J. Ji, G. Wen, and J. Richey, 2010: Crop yield responses to climate change in the Huang-Huai-Hai plain of China. *Agricultureal Water Management*, **97(8)**, 1195-1209.

Liu, Y., E. Wang, X. Yang, and J. Wang, 2009: Contributions of climatic and crop varietal changes to crop production in the North China Plain, since 1980s. *Global Change Biology*, **16(8)**, 2287-2299.

Lloyd, S.J., R.S. Kovats, and Z. Chalabi, 2011: Climate change crop yields and undernutrition: development of a model to quantify the impact of climate scenarios on child undernutrition. *Environmental Health Perspectives*, **119**, 1817-1823.

Lobell, D.B. and M.B. Burke, 2008: Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation. *Environmental Research Letters*, **3**, 034007, doi:10.1088/1748-9326/3/3/034007.

Lobell, D.B. and M.B. Burke, 2010: On the use of statistical models to predict crop yield responses to climate change. *Agricultural and Forest Meteorology*, **150**, 1443-1452.

Lobell, D.B. and C.B. Field, 2007: Global scale climate-crop yield relationships and the impacts of recent warming. *Environmental Research Letters*, **2**, 014002, doi:10.1088/1748-9326/2/1/014002.

Lobell, D.B. and C.B. Field, 2011: California perennial crops in a changing climate. *Climatic Change*, **109 (Suppl. 1)**, S317-S333.

Lobell, D.B. and J.I. Ortiz-Monasterio, 2007: Impacts of day versus night temperatures on spring wheat yields. *Agronomy Journal*, **99**, 469-477.

Lobell, D.B. , J.I. Ortiz-Monasterio, G.P. Asner, P.A. Matson, R.L. Naylor, and W.P. Falcon, 2005: Analysis of wheat yield and climatic trends in Mexico. *Field Crops Research*, **94**, 250-256.

Lobell, D.B., M.B. Burke, C. Tebaldi, M.D. Mastrandrea, W.P. Falcon, and R.L. Naylor, 2008: Prioritizing climate change adaptation needs for food security in 2030. *Science*, **319**, 607-610.

Lobell, D.B., W. Schlenker, and J. Costa-Roberts, 2011a: Climate trends and global crop production since 1980. *Science*, **333(6042)**, 616-620.

Lobell, D.B., M. Banziger, C. Magorokosho, and B. Vivek, 2011b: Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature Climate Change*, **1(1)**, 42-45.

Lobell, D.B., A. Sibley, and J.I. Ortiz-Monasterio, 2012: Extreme heat effects on wheat senescence in India. *Nature Climate Change*, **2(3)**, 186-189.

Lobell, D.B., G.L. Hammer, G. McLean, C. Messina, M.J. Roberts, and W. Schlenker, 2013a: The critical role of extreme heat for maize production in the United States. *Nature Climate Change*, **3**, 497-501.

Lobell, D.B., U.L. C. Baldos, and T.W. Hertel, 2013b: Climate adaptation as mitigation: the case of agricultural investments. *Environmental Research Letters*, **8**, 015012, doi10.1088/1748-9326/8/1/015012.

Loladze, I., 2002: Rising atmospheric CO_2 and human nutrition: toward globally imbalanced plant stoichiometry? *Trends in Ecology and Evolution*, **17**, 457-461.

Long, S.P., 2012: Virtual Special Issue on food security – greater than anticipated impacts of near-term global atmospheric change on rice and wheat. *Global Change Biology*, **18**, 1489-1490, doi: 10.1111/j.1365-2486.2012.02676.x.

Lopez, A.D., C.D. Mathers, M. Ezzati, D.T. Jamison, and C.J. Murray, 2006: Global and regional burden of disease and risk factors, 2001: systematic analysis of population health data. *The Lancet*, **367**, 1747-1757.

Luck, J., M. Spackman, A. Freeman, P. Trebicki, W. Griffiths, K. Finlay, and S. Chakraborty, 2011: Climate change and diseases of food crops. *Plant Pathology*, **60**, 113-121.

Ludwig, F., S. Milroy, and S. Asseng, 2009: Impacts of recent climate change on wheat production systems in Western Australia. *Climatic Change*, **92**, 495-517.

Luedeling, E., K.P. Steinmann, M. Zhang, P.H. Brown, J. Grant, and E.H. Girvetz, 2011: Climate change effects on walnut pests in California. *Global Change Biology*, **17**, 228-238.

Luo, Q., W. Bellotti, M. Williams, and E. Wang, 2009: Adaptation to climate change of wheat growing in South Australia: analysis of management and breeding strategies. *Agriculture Ecosystems and Environment*, **129**, 261-267.

Luo, Q., M.A.J. Williams, W. Bellotti, and B. Bryan, 2003: Quantitative and visual assessments of climate change impacts on South Australian wheat production. *Agricultural Systems*, **77(3)**, 173-186.

MacNeil, M., N. Graham, J. Cinner, N. Dulvy, P. Loring, S. Jennings, N. Polunin, A. Fisk, and T. McClanahan, 2010: Transitional states in marine fisheries: adapting to predicted global change. *Philosophical Transactions of the Royal Society B*, **365(1558)**, 3753-3763.

Mäder, P., A. Fliessbach, D. Dubois, L. Gunst, W. Jossi, F. Widmer, A. Oberson, E. Frossard, F. Oehl, A. Wiemken, A. Gattinger, and U. Niggli, 2006: The DOK Experiment (Switzerland). In: *Long-Term Field Experiments in Organic Farming* [Raupp, J., C. Pekrun, M. Oltmanns, and U. Köpke (eds.)]. International Society of Organic Agricultural Research (ISOFAR) Scientific Series No. 1, Verlag Dr. Köster, Berlin, Germany, pp. 41-58.

Mader, T.L., K.L. Frank, J.A. Harrington G.L. Hahn, and J.A. Nienaber, 2009: Potential climate change effects on warm-season livestock production in the Great Plains. *Climatic Change*, **97**, 529-541.

Magrin, G., M. Travasso, G. Rodríguez, S. Solman, and M. Núñez, 2009: Climate change and wheat production in Argentina. *International Journal of Global Warming*, **1**, 214-226.

Mandryk, M., P. Reidsma, and M.K. van Ittersum, 2012: Scenarios of long-term farm structural change for application in climate change impact assessment. *Landscape Ecology*, **27(4)**, 509-527.

Manea, A., M.R. Leishman, and P.O. Downey, 2011: Exotic C_4 grasses have increased tolerance to glyphosate under elevated carbon dioxide. *Weed Science*, **59**, 28-36.

Mantua, N., I.M. Tohver, and A.F. Hamlet, 2010: Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. *Climatic Change*, **102**, 187-223.

Marin, A., 2010: Rider under storms: contributions of nomadic herders' obervations to analysing climate change in Mongolia. *Global Environmental Change*, **20(1)**, 162-176.

Marin, F.R., J.W. Jones, A. Singels, F. Royce, E.D. Assad, G.Q. Pellegrino, and F. Justino, 2013: Climate change impacts on sugarcane attainable yield in Southern Brazil. *Climatic Change*, **117**, 227-239.

Marshall, B.E., 2012: Does climate change really explain changes in the fisheries productivity of Lake Kariba (Zambia-Zimbabwe)? *Transactions of the Royal Society of South Africa*, **67**, 45-51.

Mary, A.L. and A. Majule, 2009: Impacts of climate change, variability and adaptation strategies on agriculture in semi arid areas of Tanzania: the case of Manyoni District in Singida Region, Tanzania. *African Journal of Environmental Science and Technology*, **3**, 206-218.

Masike, S. and P. Urich, 2008: Vulnerability of traditional beef sector to drought and the challenges of climate change: the case of Kgatleng District, Botswana. *Journal of Geography and Regional Planning*, **1(1)**, 12-18.

Masike, S. and P.B. Urick, 2009: The projected cost of climate change to livestock water supply and implications in Kgatleng Districh, Botswana. *World Journal of Agricultural Sciences*, **5(5)**, 597-603.

Matthews, R. and R. Wassmann, 2003: Modelling the impacts of climate change and methane emission reductions on rice production: a review. *European Journal of Agronomy*, **19(4)**, 573-598.

Maxwell, S. and M. Smith, 1992: Part I. Household food security; a conceptual review. In: *Household Food Security: Concepts, Indicators, Measurements: A Technical Review* [Maxwell, S. and T.R. Frankenberger (eds.)]. United Nations Children's Fund (UNICEF), New York, NY, USA, and the International Fund for Agricultural Development (IFAD), Rome, Italy, pp. 1-72.

McCrum, G., K. Blackstock, K. Matthews, M. Rivington, D. Miller, and K. Buchan, 2009: Adapting to climate change in land management: the role of deliberative workshops in enhancing social learning. *Environmental Policy and Governance*, **19**, 413-426.

McDowell, J. and J. J. Hess, 2012: Accessing adaptation: multiple stressors on livelihoods in the Bolivian Highlands under a changing climate. *Global Environmental Change*, **22(2)**, 342-352.

McGrath, J.M. and D.B. Lobell, 2011: An independent method of deriving the carbon dioxide fertilization effect in dry conditions using historical yield data from wet and dry years. *Global Change Biology*, **17**, 2689-2696.

McKeon, G.M., G.S. Stone, J.I. Syktus, J.O. Carter, N.R. Floof, D.G. Ahrens, D.N. Bruget, C.R. Chilcott, D.H. Cobon, R.A. Cowley, S.J. Crimp, G.W. Fraser, S.M. Howden, P.W. Johnston, J.G. Ryan, C.J. Stokes, and K.A. Day, 2009: Climate change impacts on northern Australian rangeland livestock carrying capacity: a review of issues. *The Rangeland Journal*, **31**, 1-29.

Melloy, P., G. Hollaway, J. Luck, R. Norton, E. Aitken, and S. Chakraborty, 2010: Production and fitness of *Fusarium pseudograminearum inoculum* at elevated carbon dioxide in FACE. *Global Change Biology*, **16**, 3363-3373.

Mercer, K., A. Martinez-Vasquez, and H. Perales, 2008: Asymmetrical local adaptation of maize landraces along an altitudinal gradient. *Evolutionary Applications*, **1**, 489-500.

Merino, G., M. Barange, J.L. Blanchard, J. Harle, R. Holmes, I. Allen, E.H. Allison, M.C. Badjeck, N.K. Dulvy, J. Holt, S. Jennings, C. Mullon, and L.D. Rodwell, 2012: Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate? *Global Environmental Change*, **22**, 795-806.

Mertz, O., K. Halsnaes, J. Olesen, and K. Rasmussen, 2009a: Adaptation to climate change in developing countries. *Environmental Management*, **43**, 743-752.

Mertz, O., C. Mbow, A. Reenberg, and A. Diouf, 2009b: Farmers' perceptions of climate change and agricultural adaptation strategies in rural Sahel. *Environmental Management*, **43**, 804-816.

Meza, F. and D. Silva, 2009: Dynamic adaptation of maize and wheat production to climate change. *Climatic Change*, **94(1-2)**, 143-156.

Meza, F., D. Silva, and H. Vigil, 2008: Climate change impacts on irrigated maize in Mediterranean climates: evaluation of double cropping as an emerging adaptation alternative. *Agricultural Systems*, **98**, 21-30.

Mills, G., A. Buse, B. Gimeno, V. Bermejo, M. Holland, L. Emberson, and H. Pleijel, 2007: A synthesis of AOT40-based response functions and critical levels of ozone for agricultural and horticultural crops. *Atmospheric Environment*, **41**, 2630-2643.

Mills, G., F. Hayes, S. Wilkinson, and W.J. Davies, 2009: Chronic exposure to increasing background ozone impairs stomatal functioning in grassland species. *Global Change Biology*, **15**, 1522-1533.

Mills, J.N., K.L. Gage, and A.S. Khan, 2010: Potential influence of climate change on vector-borne and zoonotic diseases: a review and proposed research plan. *Environmental Health Perspectives*, **118(11)**, 1507-1514.

Min, S., X. Zhang, F.W. Zwiers, and G.C. Hegerl, 2011: Human contribution to more-intense precipitation extremes. *Nature*, **470**, 378-381.

Miraglia, M., H.J.P. Marvin, G.A. Kleter, P. Battilani, C. Brera, E. Coni, F. Cubadda, L. Croci, B. De Santis, S. Dekkers, L. Filippi, R.W. Hutjes, M.Y. Noordam, M. Pisante, G. Piva, A. Prandini, L. Toti, G.J. van den Born, and A. Vespermann, 2009: Climate change and food safety: an emerging issue with special focus on Europe. *Food and Chemical Toxicology*, **47(5)**, 1009-1021.

Misselhorn, A., A. Challinor, P. Thornton, J.W. Jones, R. Schaldach, and V. Plocq-Fichelet, 2010: Chapter 20: Surprises and possibilities. In: *Food Security and Global Environmental Change* [Ingram, J., P. Ericksen, and D. Liverman (eds.)]. Earthscan, London, UK and Washington, DC, USA, pp. 318-341.

Mo, X., S. Liu, Z. Lin, and R. Guo, 2009: Regional crop yield, water consumption and water use efficiency and their responses to climate change in the North China Plain. *Agriculture, Ecosystems & Environment*, **134**, 67-78.

Molden, D., T. Oweis, P. Steduto, P. Bindraban, M.A. Hanjra, and J. Kijne, 2010: Improving agricultural water productivity: between optimism and caution. *Agricultural Water Management*, **97**, 528-535.

Monzon, J.P., V.O. Sadras, P.A. Abbate, and O.P. Caviglia, 2007: Modelling management strategies for wheat-soybean double crops in the south-eastern pampas. *Field Crops Research*, **101(1)**, 44-52.

Moore, A.D. and A. Gharamani, 2013: Climate change and broadacre livestock production across Southern Australia: II. Impacts of climate change on pasture and livestock productivity, and on sustainable level of profitability. *Global Change Biology*, **19**, 1440-1455.

Morgan, P.B., T.A. Mies, G.A. Bollero, R.L. Nelson, and S.P. Long, 2006: Season long elevation of ozone concentration to projected 2050 levels under fully open air conditions substantially decreases the growth and production of soybean. *New Phytologist*, **170**, 333-343.

Moriondo, M., M. Bindi, Z. Kundzewicz, M. Szwed, A. Chorynski, P. Matczak, M. Radziejewski, D. McEvoy, and A. Wreford, 2010: Impact and adaptation opportunities for European agriculture in response to climatic change and variability. *Mitigation and Adaptation in Strategies for Global Change*, **15**, 657-679.

Moriondo, M., C. Giannakopoulos, and M. Bindi, 2011: Climate change impact assessment: the role of climate extremes in crop yield simulation. *Climatic Change*, **104**, 679-701.

Mortensen, C.J., Y.H. Choi, K. Hinrichs, N.H. Ing, D.C. Kraemer, S.G. Vogelsang, and M.M. Vogelsang, 2009: Embryo recovery from exercised mares. *Animal Reproduction Science*, **110(3-4)**, 237-244.

Moya, T.B., L.H. Ziska, O.S. Namuco, and D. Olszyk, 1998: Growth dynamics and genotypic variation in tropical, field-grown paddy rice (*Oryza sativa* L.) in response to increasing carbon dioxide and temperature. *Global Change Biology*, **4(6)**, 645-656.

Müller, C., A. Bondeau, A. Popp, K. Waha, and M. Fadar, 2010: *Climate Change Impacts on Agricultural Yields*. Background note for the *World Development Report 2010: Development and Climate Change*, Potsdam Institute for Climate Impact Research (PIK), The World Bank, Washington, DC, USA, 11 pp.

Müller, C. and R.D. Robertson, 2014: Projecting future crop productivity for global economic modeling. *Agricultural Economics*, **45**, 37–50.

Mueller, S., J. Anderson, and T. Wallington, 2011: Impact of biofuel production and other supply and demand factors on food price increases in 2008. *Biomass and Bioenergy*, **35**, 1623-1632.

Munday, P.L., G.P. Jones, M.S. Pratchett, and A.J. William, 2008: Climate change and the future for coral reef fishes. *Fish and Fisheries*, **9(3)**, 261-285.

Mutekwa, V., 2009: Climate change impacts and adaptation in the agricultural sector: the case of smallholder farmers in Zimbabwe. *Journal of Sustainable Development in Africa*, **11**, 237-256.

Nakashina, D., K. Galloway McLean, H.D. Thulstrup, A. Ramos Castillo, and J.T. Rubis, 2012: *Weathering Uncertainty: Traditional Knowledge for Climate Change Assessment and Adaptation*. United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris, France, and the United Nations University (UNU), Darwin, Australia, 120 pp.

Natkhin, M., O. Dietrich, M.P. Schafer, and G. Lischeid, 2013: The effects of climate and changing land use on the discharge regime of a small catchment in Tanzania. *Regional Environmental Change*, doi:10.1007/s10113-013-0462-2.

Nardone, A., B. Ronchi, N. Lacetera, M.S. Ranieri, and U. Bernabucci, 2010: Effects of climate changes on animal production and sustainability of livestock systems. *Livestock Science*, **130(1)**, 57-69.

Naylor, R., D. Battisti, D. Vimont, W. Falcon, and M. Burke, 2007: Assessing risks of climate variability and climate change for Indonesian rice agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, **104**, 7752-7757.

Ndebele-Murisa, M., E. Mashonjowa, and T. Hill, 2011: The Implications of a changing climate on the Kapenta fish stocks of Lake Kariba, Zimbabwe. *Transactions of the Royal Society of South Africa*, **66(2)**, 105-119.

Nelson, G.C., M.W. Rosegrant, J. Koo, R. Robertson, T. Sulser, T. Zhu, C. Ringler, S. Msangi, A. Palazzo, M. Batka, M. Magalhaes, R. Valmonte-Santos, M. Ewing, and D. Lee, 2009: *Climate Change: Impact on Agriculture and Costs of Adaptation*. Food Policy Report, International Food Policy Research Institute (IFPRI), Washington DC, USA, 19 pp.

Nelson, G. C., H. Valin, R. D. Sands, P. Havlík, H. Ahammad, D. Deryng, J. Elliott, S. Fujimori, T. Hasegawa, E. Heyhoe, P. Kyle, M. Von Lampe, H. Lotze-Campen, D. Mason d'Croz, H. van Meijl, D. van der Mensbrugghe, C. Müller, A. Popp, R. Robertson, S. Robinson, E. Schmid, C. Schmitz, A. Tabeau and D. Willenbockel, 2013: Climate Change Effects on Agriculture: Economic Responses to Biophysical Shocks. *Proceedings of the National Academy of Sciences of the United States of America*. doi: 10.1073/pnas.1222465110.

Nelson, G.C., D. van der Mensbrugghe, T. Hasegawa, K. Takahashi, R.D. Sands, P. Kyle, H. Lotze-Campen, M. von Lampe, D.M. d'Croz, H. van Meijl, C. Müller, J. Reilly, R. Robertson, R.D. Sands, C. Schmitz, A. Tabeau, K. Takahashi, H. Valin, and D. Willenbockel, 2014: Agriculture and climate change in global scenarios: why don't the models agree? *Agricultural Economics*, **45 (1)**, 85–101.

Nelson, R., M. Howden, and M. Stafford Smith, 2008: Using adaptive governance to rethink the way science supports Australian drought policy. *Environmental Science & Policy*, **11(17)**, 588-601.

Newsham, A. J. and D. Thomas, 2011: Knowing, farming and climate change adaptation in North-Central Namibia. *Global Environmental Change*, **21(2)**, 761-770.

Nesamvuni, E., R. Lekalakala, D. Norris, and J.W. Ngambi, 2012: Effects of climate change on dairy cattle, South Africa. *African Journal of Agricultural Research*, **7(26)**, 3867-3872.

Nidumolu, U.B., P.T. Hayman, S.M. Howden, and B.M. Alexander, 2012: Re-evaluating the margin of the South Australian grain belt in a changing climate. *Climate Research*, **51**, 249-260.

Nidumolu, U., S. Crimp, D. Gobbett, A. Laing, S.M. Howden, and S. Little, 2013: Spatio-temporal modelling of heat stress and climate change implications for the Murray dairy region, Australia. *International Journal of Biometeorology*, DOI 10.1007/s00484-013-0703-6.

Nyong, A., F. Adesina, and B. Elasha, 2007: The value of indigenous knowledge in climate change mitigation and adaptation strategies in the African Sahel. *Mitigation and Adaptation Strategies for Global Change*, **12**, 787-797.

Odgaard, M., P. Bøcher, T. Dalgaard, and J. Svenning, 2011: Climate and non-climatic drivers of spatiotemporal maize-area dynamics across the northern limit for maize production – a case study from Denmark. *Agriculture Ecosystems and Environment*, **142**, 291-302.

Oerke, E.C., 2006: Crop losses to pests. *The Journal of Agricultural Science*, **144**, 31-43.

Okada, M., T. Lizumi, Y. Hayashi, and M. Yokozawa, 2011: Modeling the multiple effects of temperature and radiation on rice quality. *Environmental Research Letters*, **6(3)**, 034031, doi:10.1088/1748-9326/6/3/034031.

Olesen, J.E., M. Trnka, K. Kersebaum, A. Skjelvåg, B. Seguin, P. Peltonen-Sainio, F. Rossi, J. Kozyra, and F. Micale, 2011: Impacts and adaptation of European crop production systems to climate change. *European Journal of Agronomy*, **34(2)**, 96-112.

Olesen, J.E., T.R. Carter, C.H. Diaz-Ambrona, S. Fronzek, T. Heidmann, T. Hickler, T. Holt, M.I. Minguez, P. Morales, J.P. Palutikof, M. Quemada, M. Ruiz-Ramos, G.H. Rubaek, F. Sao, B. Smith, and M.T. Sykes, 2007: Uncertainties in projected impacts of climate change on European agriculture and terrestrial ecosystems based on scenarios from regional climate models. *Climatic Change*, **81(2)**, 123-143.

O'Reilly, C.M., S.R. Alin, P.D. Plisnier, A.S. Cohen, and B.A. McKee, 2003: Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa. *Nature*, **424**, 766-768.

Orlandini, S., M. Bindi, and S. Howden, 2008: Plant biometeorology and adaptation. In: *Biometeorology for Adaptation to Climate Variability and Change: Research Frontiers and Perspectives* [Ebi, K., I. Burton, and G. McGregor (eds.)]. Springer, Dordrecht, Netherlands, pp. 107-129.

Ortiz, R., K.D. Sayre, B. Govaerts, R. Gupta, G.V. Subbarao, T. Ban, D. Hodson, J.M. Dixon, J. Iván Ortiz-Monasterio, and M. Reynolds, 2008: Climate change: can wheat beat the heat? *Agriculture, Ecosystems & Environment*, **126**, 46-58.

Osborne, T.M., D.M. Lawrence, A.J. Challinor, J.M. Slingo, and T.R. Wheeler, 2007: Development and assessment of a coupled crop-climate model. *Global Change Biology*, **13**, 169-183.

Osborne, T.M., G. Rose, and T. Wheeler, 2013: Variation in the global-scale impacts of climate change on crop productivity due to climate model uncertainty and adaptation. *Agricultural and Forest Meteorology*, **170**, 183-194.

Paavola, J., 2008: Livelihoods, vulnerability and adaptation to climate change in Morogoro, Tanzania. *Environmental Science & Policy*, **11**, 642-654.

Palmer, M.A., C.A. Reidy Liermann, C. Nilsson, M. Florke, J. Alcamo, P.S. Lake, and N. Bond, 2008: Climate change and the world's river basins: anticipating management options. *Frontiers in Ecology and the Environment*, **6**, 81-89.

Palosuo, T., K.C. Kersebaum, C. Angulo, P. Hlavinka, M. Moriondo, J.E. Olesen, R.H. Patil, F. Ruget, C. Rumbaur, J. Takáč, M. Trnka, M. Bindi, B. Çaldağ, F. Ewert, R. Ferrise, W. Mirschel, L. Saylan, B. Šiška, and R. Rötter, 2011: Simulation of winter wheat yields and yield variability in different climates of Europe. A comparison of eight crop growth models. *European Journal of Agronomy*, **35**, 103-114.

Pareek, A. and P. Trivedi, 2011: Cultural values and indigenous knowledge of climate change and disaster prediction in Rajasthan India. *Indian Journal of Traditional Knowledge*, **10**, 183-189.

Park, S., N. Marshall, E. Jakku, A. Dowd, S. Howden M., E. Mendham, and A. Fleming, 2012: Informing adaptation responses to climate change through theories of transformation. *Global Environmental Change*, **22**, 115-126.

Parry, M., A. Evans, M.W. Rosegrant, and T. Wheeler, 2009: *Climate Change and Hunger: Responding to the Challenge*. World Food Programme (WFP), Rome, Italy, 104 pp.

Passioura, J. and J. Angus, 2010: Chapter 2: Improving productivity of crops in water-limited environments. In: *Advances in Agronomy, Vol. 106* [Sparks, D.L. (ed.)]. Elsevier Science and Technology/Academic Press, Waltham, MA, USA, pp. 37-75.

Pathak, H., J.K. Ladha, P.K. Aggarwal, S. Peng, S. Das, Y. Singh, B. Singh, S.K. Kamra, B. Mishra, A. Sastri, H.P. Aggarwal, D.K. Das, and R.K. Gupta, 2003: Trends of climatic potential and on-farm yields of rice and wheat in the Indo-Gangetic Plains. *Field Crops Research*, **80**, 223-234.

Paulson, M.D., A.I. Houston, J.M. McNamara, and R.J.H. Payne, 2009: Seasonal dispersal of pests: one surge or two? *Journal of Evolutionary Biology*, **22**, 1193-1202.

Pautasso, M., K. Dehnen-Schmutz, O. Holdenrieder, S. Pietravalle, N. Salama, M.J. Jeger, E. Lange, and S. Hehl-Lange, 2010: Plant health and global change – some implications for landscape management. *Biological Reviews of the Cambridge Philosophical Society*, **85**, 729-755.

Peltonen-Sainio, P., L. Jauhiainen, and K. Hakala, 2011: Crop responses to temperature and precipitation according to long-term multi-location trials at high-latitude conditions. *The Journal of Agricultural Science*, **149(1)**, 49-62.

Peng, S., J. Huang, J. Sheehy, R. Laza, R. Visperas, X. Zhong, G. Centeno, G. Khush, and K. Cassman, 2004: Rice yields decline with higher night temperature from global warming. *Proceedings of the National Academy of Sciences of the United States of America*, **101**, 9971-9975.

Perring, M.P., B.R. Cullen, I.R. Johnson, and M.J. Hovenden, 2010: Modelled effects of rising CO_2 concentration and climate change on native perennial grass and sown grass-legume pastures. *Climate Research*, **42**, 65-78.

Perry, A.L., P.J. Low, J.R. Ellis, and J.D. Reynolds, 2005: climate change and distribution shifts in marine fishes. *Science*, **308**, 1912-1915.

Pfeffer, M. and G. Dobler, 2010: Emergence of zoonotic arboviruses by animal trade and migration. *Parasites & Vectors*, **3(35)**, doi:10.1186/1756-3305-3-35.

Piao, S., P. Ciais, Y. Huang, Z. Shen, S. Peng, J. Li, L. Zhou, H. Liu, Y. Ma, Y. Ding, P. Friedlingstein, C. Liu, K. Tan, Y. Yu, T. Zhang, and J. Fang, 2010: The impacts of climate change on water resources and agriculture in China. *Nature*, **467**, 43-51.

Pickering, T.D., B. Ponia, C.A. Hair, P.C. Southgate, and E.S. Poloczanska, 2011: Vulnerability of aquaculture in the tropical Pacific to climate change. In: *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change* [Bell, J.D., J.E. Johnson, and A.J. Hobday (eds.)]. Secretariat of the Pacific Community, Noumea, New Caledonia, pp. 647-731.

Pikki, K., V. Vorne, K. Ojanpera, and H. Pleijel, 2007: Impact of elevated O_3 and CO_2 exposure on potato (*Solanum tuberosum* L. cv. Bintje) tuber macronutrients (N, P, K, Mg, Ca). *Agriculture, Ecosystems and Environment*, **118(1-4)**, 55-64.

Pinstrup-Andersen, P., 2009: Food security: definition and measurement. *Food Security*, **1**, 5-7.

Pinto, H.S., J. Zullo Jr., E.D.Assad, and B.A. Evangelista, 2007: O aquecimento global e a cafeicultura brasileira. *Boletim da Sociedade Brasileira de Meteorologia*, **31**, 65-72.

Pinto, H.S., E.D. Assad, J.Z. Junior, S. Evangelista, A. Otavian, A. Ávila, B. Evangelista, F. Marin, C. Junior, G.Q. Pellegrino, P. Coltri, and G. Coral, 2008: *Global Warming and the New Geography of Agricultural Production in Brazil*. Centro de Pesquisas Meteorológicas e Climáticas Aplicadas à Agricultura (CEPAGRI) and Brazilian Agricultural Research Corporation (EMBRAPA), Sao Paulo, Brazil, 83 pp.

Pleijel, H. and J. Uddling, 2012: Yield vs. quality trade-offs for wheat in response to carbon dioxide and ozone. *Global Change Biology*, **18**, 596-605.

Porter, J.R. and M. Gawith, 1999: Temperatures and the growth and development of wheat: a review. *European Journal of Agronomy*, **10**, 23-36.

Porter, J.R. and M.A. Semenov, 2005: Crop responses to climatic variation. *Philosophical Transactions of the Royal Society B*, **360(1463)**, 2021-2035.

Prakash, A., 2011: Why volatility matters. In: *Safeguarding Food Security in Volatile Global Markets* [Prakash, A. (ed.)]. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, pp. 3-26.

Pratchett, M.S., P.L. Munday, N.A.J. Graham, M. Kronen, S. Pinca, K. Friedman, T.D. Brewer, J.D. Bell, S.K. Wilson, J.E. Cinner, J.P. Kinch, R.J. Lawton, A.J. Williams, L.

Chapman, F. Magron, and A. Webb, 2011: Vulnerability of coastal fisheries in the tropical Pacific to climate change. In: *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change* [Bell, J.D., J.E. Johnson, and A.J. Hobday (eds.)]. Secretariat of the Pacific Community, Noumea, New Caledonia, pp. 493-573.

Prato, T., Q. Zeyuan, G. Pederson, D. Fagre, L. Bengtson, and J. Williams, 2010: Potential economic benefits of adapting agricultural production systems to future climate change. *Environmental Management*, **45**, 577-589.

Pritchard, S.G., 2011: Soil organisms and global climate change. *Plant Pathology*, **60**, 82-99.

Rai, R., M. Aggarwal, and S.B. Aggarwal, 2010: Threat to food security under current levels of ground level ozone: a case study for Indian cultivars of rice. *Atmospheric Environment*, **44**, 4272-4282.

Ramirez-Villegas, J.M., A. Salazar, C. Jarvis, and E. Navarro-Racines, 2012: A way forward on adaptation to climate change in Colombian agriculture: perspectives towards 2050. *Climatic Change*, **115**, 611-628.

Ramirez-Villegas, J., A.J. Challinor, P.K. Thornton, and A. Jarvis, 2013: Implications of regional improvement in global climate models for agricultural impact research. *Environmental Research Letters*, **8(2)**, 024018, doi:10.1088/1748-9326/8/2/024018.

Ravallion, M. and C. Shaohua, 2007: China's (uneven) progress against poverty. *Journal of Development Economics*, **82**, 1-42.

Rayne, S., K. Forest, and K. Friesen, 2009: Projected climate change impacts on grape growing in the Okanagan Valley, British Columbia, Canada. *Nature Precedings*, doi: 10.1038/npre.2011.3162.2.

Reidsma, P. and F. Ewert, 2008: Regional farm diversity can reduce vulnerability of food production to climate change. *Ecology and Society*, **13(1)**, 38.

Reidsma, P., F. Ewert, L. Oude A., and R. Leemans, 2009: Vulnerability and adaptation of European farmers: a multi-level analysis of yield and income responses to climate variability. *Regional Environmental Change*, **9(1)**, 25-40.

Renard, D., J. Iriarte, J. Birk, S. Rostain, B. Glaser, and D. McKey, 2011: Ecological engineers ahead of their time: the functioning of pre-Columbian raised-field agriculture and its potential contributions to sustainability today. *Ecological Engineering*, **45**, 30-44.

Renaudeau, D., J. Gourdine, and N. St-Pierre, 2011: A meta-analysis of the effects of high ambient temperature on growth performance of growing-finishing pigs. *Journal of Animal Science*, **89**, 2220-2230.

Rengalakshmi, R., 2007: Localized climate forecasting system: seasonal climate and weather prediction for farm-level decision-making. In: *Climate Predictions and Agriculture: Advances and Challenges* [Sivakumar, M. and J. Hansen (eds.)]. World Meteorological Organization (WMO), Springer-Verlag, Berlin, Heidelberg, Germany, pp. 129-134.

Reyenga, P.J., S.M. Howden, H. Meinke, and G.M. McKeon, 1999: Modelling global change impacts on wheat cropping in south-east Queensland, Australia, *Environmental Modeling and Software*, **14**, 297-306.

Rickards, L. and S.M. Howden, 2012: Transformational adaptation: agriculture and climate change. *Crop and Pasture Science*, **63**, 240-250.

Ringler, C., T. Zhu, X. Cai, J. Koo, and D. Wang, 2010: *Climate Change Impacts on Food Security in Sub-Saharan Africa*. IFPRI Discussion Paper No. 01042, International Food Policy Research Institute (IFPRI), Washington DC, USA, 17 pp.

Roberts, M.J. and W. Schlenker, 2010: *Identifying Supply and Demand Elasticities of Agricultural Commodities: Implications for the US Ethanol Mandate*. NBER Working Paper No. 15921, The National Bureau of Economic Research (NBER), Cambridge, MA, USA, 46 pp.

Rocque, S.D.L., J.A. Rioux, and J. Singenbergh, 2008: Climate change: effects on animal disease systems and implications for surveillance and control. *Revue Scientifique et Technique (Office International des Epizooties)*, **27**, 339-354.

Roe, T. and T. Graham-Tomasi, 1986: Yield risk in a dynamic model of the agricultural household. In: *Agricultural Household Models: Extension, Applications and Policy* [Singh, I., L. Squire, and J. Strauss (eds.)]. A World Bank Research Publication, Johns Hopkins University Press, Baltimore, MD, USA, pp. 255-276.

Rosenberg, A. and K. Macleod, 2005: Implementing ecosystem-based approaches to management for the conservation of ecosystem services. *Marine Ecology Progress Series*, **300**, 270-274.

Rosenthal, D. and D.R. Ort, 2012: Examining cassava's potential to enhance food security under climate change. *Tropical Plant Biology*, **5**, 30-38.

Rosenthal, J., 2009: Climate change and the geographic distribution of infectious diseases. *Ecohealth*, **6**, 489-495.

Rosenzweig, C. and M.L. Parry, 1994: Potential impact of climate change on world food supply. *Nature*, **367**, 133-138.

Rosenzweig, C., F.N. Tubiello, R. Goldberg, E. Mills, and J. Bloomfield, 2002: Increased crop damage in the US from excess precipitation under climate change. *Global Environmental Change: Human and Policy Dimensions*, **12**, 197-202.

Rosenzweig, C., J. Elliott, D. Deryng, A.C. Ruane, C. Müller, A. Arneth, and J.W. Jones, 2014: Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences*, 201222463.

Rosenzweig, C., J.W. Jones, J.L. Hatfield, A.C. Ruane, K.J. Boote, P. Thorburn, J.M. Antle, G.C. Nelson, C. Porter, S. Janssen, S. Asseng, B. Basso, F. Ewert, D. Wallach, G. Baigorria, and J.M. Winter, 2013: The Agricultural Model Intercomparison and Improvement Project (AgMIP): protocols and pilot studies. *Agricultural and Forest Meteorology*, **170**, 166-182.

Rosenzweig, M.R. and H.P. Binswanger, 1993: Wealth, weather risk and the composition and profitability of agricultural investments. *Economic Journal*, **103**, 56-78.

Rötter, R.P., T. Palosuo, N.K. Pirttioja, M. Dubrovsky, T. Salo, S. Fronsek, R. Aikasalo, M. Trnka, A. Ristolainen, and T. Carter, 2011: What would happen to barley production in Finland if global warming exceeded 4°C? A model-based assessment. *European Journal of Agronomy*, **35**, 205-214.

Rowhanji, P., D. Lobell, M. Lindermann, and N. Ramankutty, 2011: Climate variability and crop production in Tanzania. *Agriculture and Forest Meteorology*, **151**, 449-460.

Roy, S., G. Beig, and S. Ghude, 2009: Exposure-plant response of ambient ozone over the tropical Indian region. *Atmospheric Chemistry and Physics*, **9**, 5253-5260.

Royal Society, 2008: *Ground Level Ozone in the 21st Century: Future Trends, Impacts and Policy Implications*. Science Policy Document 15/08, The Royal Society, London, UK, 131 pp.

Ruane, A.C., L.D. Cecil, R.M. Horton, R. Gordón, R. McCollum, B. Brown, B. Killough, R. Goldberg, A.P. Greeley, and C. Rosenzweig, 2013: Climate change impact uncertainties for maize in Panama: farm information, climate projections, and yield sensitivities. *Agricultural and Forest Meteorology*, **170**, 132-145.

Sadras, V.O. and P.R. Petrie, 2011: Climate shifts in south-eastern Australia: early maturity of Chardonnay, Shiraz and Cabernet Sauvignon is associated with early onset rather than faster ripening. *Australian Journal of Grape and Wine Research*, **17**, 199-205.

Sakurai, G., T. Lizumi, and M. Yokozawa, 2012: Varying temporal and spatial effects of climate on maize and soybean affect yield prediction. *Climate Research*, **49**, 143-154.**3**

Salick, J. and N. Ross, 2009: Introduction.Traditional peoples and climate change. *Global Environmental Change*, **19**, 137-139.

Sánchez, B., A. Rasmussen, and J.R. Porter, 2014: Temperatures and the growth and development of maize and rice: a review. *Global Change Biology*, **20**, 408–417.

Sands, R.D. and J.A. Edmonds, 2005: Climate change impacts for the conterminous USA: an integrated assessment. Part 7. Economic analysis of field crops and land use with climate change. *Climatic Change*, **69**, 127-150.

Santos, J.A., A.C. Malheiro, M.K. Karremann, and J.G. Pinto, 2011: Statistical modelling of grapevine yield in the Port Wine region under present and future climate conditions. *International Journal of Biometeorology*, **55**, 119-131.

Sari, M., S. de Pee, M.W. Bloem, K. Sun, A. Thorne-Lymean, R. Moench-Pfanner, N. Akhter, K. Kraemer, and R.D. Semba, 2010: Higher household expenditure on animal source and nongrain foods lowers the risk of stunting among children 0-59 months old in Indonesia: implications of rising food prices. *The Journal of Nutrition*, **140(Suppl. 1)**, 195S-200S.

Sarkar, A. and S.B. Agrawal, 2010: Elevated ozone and two modern wheat cultivars: an assessment of dose dependent sensitivity with respect to growth, reproductive and yield parameters. *Environmental and Experimental Botany*, **69**, 328-337.

Sarvala, J., V.T. Langenberg, K. Salonen, D. Chitamwebwa, G.W. Coulter, T. Huttula, R. Kanyaru, P. Kotilainen, S. Makasa, N. Mulimbwa, and H. Molsa, 2006: Fish catches from Lake Tanganyika mainly reflect changes in fishery practices, not climate. *Verhandlungen Internationale Vereinigung für Theoretische und Angewandte Limnologie*, **29**, 1182-1188.

Savary, S., N.P. Castilla, F.A. Elazegui, and P.S. Teng, 2005: Multiple effects of two drivers of agricultural change, labour shortage and water scarcity, on rice pest profiles in tropical Asia. *Field Crops Research*, **91**, 263-271.

Savary, S., A. Mila, L. Willocquet, P.D. Esker, O. Carisse, and N. McRoberts, 2011: Risk factors for crop health under global change and agricultural shifts: a framework of analyses using rice in tropical and subtropical Asia as a model. *Phytopathology*, **101**, 696-709.

Schaefleitner, R., J. Ramirez, A. Jarvis, D. Evers, R. Gutierrez, and M. Scurrah, 2011: Adaptation of the potato crop to changing climates. In: *Crop Adaptation to Climate Change* [Yadav, S., B. Redden, J.L. Hattfield, and H. Lotze-Campen (eds.)]. Wiley-Blackwell, Oxford, UK, pp. 287-297.

Scherm, H. and X.B. Yang, 1995: Interannual variations in wheat rust development in China and the United States in relation to the El Niño/Southern Oscillation. *Phytopathology*, **85**, 970-976.

Schlenker, W. and D. Lobell, 2010: Robust negative impacts of climate change on African agriculture. *Environmental Research Letters*, **5(1)**, 014010, doi:10.1088/1748-9326/5/1/014010.

Schlenker, W. and M.J. Roberts, 2009: Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **106(37)**, 15594-15598.

Schroth, G., P. Laderach, J. Dempewolf, S. Philpott, J. Haggar, H. Eakin, T. Castillejos, M. Garcia, L. Soto Pinto, R. Hernandez, A. Eitzinger, and J. Ramirez-Villegas, 2009: Towards a climate change adaptation strategy for coffee communities and ecosystems in the Sierra Madre de Chiapas, Mexico. *Mitigation and Adaptation Strategies for Global Change*, **14**, 605-626.

Semenov, M., R. Mitchell, A. Whitmore, M. Hawkesford, M. Parry, and P. Shewry, 2012: Shortcoming in wheat yield productions. *Nature Climate Change*, **2**, 380-382.

Seo, S., 2010: Is an integrated farm more resilient against climate change? A micro-econometric analysis of portfolo diversification in African agriculture. *Food Policy*, **35**, 32-40.

Seo, S. and R. Mendelsohn, 2008: Measuring impacts and adaptations to climate change: a structural Ricardian model of African livestock management-super-1. *Agricultural Economics*, **38**, 151-165.

Seo, S., B.A. McCarl, and R. Mendelsohn, 2010: From beef cattle to sheep under global warming? An analysis of adaptation by livestock species choice in South America. *Ecological Economics*, **69**, 2486-2494.

Shaw, M.W., S.J. Bearchell, B.D.L. Fitt, and B.A. Fraaije, 2008: Long-term relationships between environment and abundance in wheat of *Phaeosphaeria nodorum* and *Mycosphaerella graminicola*. *New Phytologist*, **177(1)**, 229-238.

Shen, S.-H., S.-B. Yang, Y.-X. Zhao, Y.-L. Xu, X.-Y. Zhao, Z.-Y. Wang, J. Liu, and W.-W. Zhang, 2011: Simulating the rice yield change in the middle and lower reaches of the Yangtze River under SRES B2 scenario. *Acta Ecologica Sinica*, **31(1)**, 40-48.

Shimono, H., M. Okada, Y. Yamakawa, H. Nakamura, K. Kobayashi, and T. Hasegawa, 2008: Rice yield enhancement by elevated CO_2 is reduced in cool weather. *Global Change Biology*, **14**, 276-284.

Shimono, H., H. Kanno, and S. Sawano, 2010: Can the cropping schedule of rice be adapted to changing climate? A case study in cool areas of northern Japan. *Field Crops Research*, **118**, 126-134.

Shuang-He, S., Y. Shen-Bin, Z. Yan-Xia, X. Yin-Long, Z. Xiao-Yan, W. Zhu-Yu, L. Juan, and Z. Wei-Wei, 2011: Simulating the rice yield change in the middle and lower reaches of the Yangtze River under SRES B2 scenario. *Acta Ecologica Sinica*, **31**, 40-48.

Silva, T.G.F., M.S.B. Moura, I.I.S. Sá, S. Zolnier, S.H.N. Turco, F. Justino, J.F.A. Carmo, and L.S.B. Souza, 2009: Impactos das mudanças climáticas na produção leiteira do estado de Pernambuco: análise para os cenários B2 e A2 do IPCC: (Impacts of climate change on regional milk production in the Pernambuco State, Brazil: analysis for the A2 and B2 IPCC scenarios). *Revista Brasileira de Metreologia*, **24**, 4, 489-501.

Silvestri, S., E. Bryan, C. Ringler, M. Herrero, and B. Okoba, 2012: Climate change perception and adaptation of agro-pastoral communities in Kenya. *Regional Environmental Change*, **12(4)**, 791-802.

Skees, J., P. Hazell, and M. Miranda, 1999: *New Approaches to Crop Yield Insurance in Developing Countries*. Environmental and Production Technology Division (EPTD) Discussion Paper No. 55, International Food Policy Research Institute (IFPRI), Washington, DC, USA, 40 pp.

Skoufias, E. and A.R. Quisumbing, 2005: Consumption insurance and vulnerability to poverty: a synthesis of the evidence from Bangladesh, Ethiopia, Mali, Mexico and Russia. *European Journal of Development Research*, **17**, 24-58.

Smit, B. and J. Wandel, 2006: Adaptation, adaptive capacity and vulnerability. *Global Environmental Change*, **16**, 282-292.

Smith, L., H. Alderman, and D. Aduayom, 2006: *Food Insecurity in Sub-Saharan Africa: New Estimates from Household Expenditure Survey*. IFPRI Research Report No. 146, International Food Policy Research Institute (IFPRI), Washington DC, USA, 122 pp.

Smith, P. and J. Olesen, 2010: Synergies between the mitigation of, and adaptation to, climate change in agriculture. *Journal of Agricultural Science*, **148(5)**, 543-552.

Smith, P., P.J. Gregory, D. van Vuren, M. Obersteiner, P. Havlik, M. Rounsevell, J. Woods, E. Stehfest, and J. Bellarby, 2010: Competition for land. *Philosophical Transactions of the Royal Society B*, **365**, 2941-2957.

Soltani, A. and G. Hoogenboom, 2007: Assessing crop management options with crop simulation models based on generated weather data. *Field Crops Research*, **103**, 198-207.

Soussana, J., A. Graux, and F.N. Tubiello, 2010: Improving the use of modelling for projections of climate change impacts on crops and pastures. *Journal of Experimental Botany*, **61**, 2217-2228.

Southworth, J., J.C. Randolph, M. Habeck, O.C. Doering, R.A. Pfeifer, D.G. Rao, and J.J. Johnston, 2000: Consequences of future climate change and changing climate variability on maize yields in the midwestern United States. *Agriculture, Ecosystems & Environment*, **82**, 139-158.

Speranza, C.I., B. Kiteme, P. Ambenje, U. Wiesmann, and S. Makali, 2010: Indigenous knowledge related to climate change variability and change: insights from droughts in semi-arid areas of former Makueni Distict, Kenya. *Climatic Change*, **100**, 295-315.

Srivastava, A., S. Naresh Kumar, and P.K. Aggarwal, 2010: Assessment on vulnerability of sorghum to climate change in India. *Agriculture, Ecosystems and Environment*, **138(3-4)**, 160-169.

St. Clair, S.B. and J.P. Lynch, 2010: The opening of Pandora's Box: climate change impacts on soil fertility and crop nutrition in developing countries. *Plant and Soil*, **335**, 101-115.

Stathers, T., R. Lamboll, and B.M. Mvumi, 2013: Postharvest agriculture in changing climates: its importance to African smallholder farmers. *Food Security*, **5**, 361-392.

Stöckle, C.O., R.L. Nelson, S. Higgins, J. Brunner, G. Grove, R. Boydston, M. Whiting, and C. Kruger, 2010: Assessment of climate change impact on Eastern Washington agriculture. *Climatic Change*, **102**, 77-102.

Sultana, H., N. Ali, M.M. Iqbal, and A.M. Khan, 2009: Vulnerability and adaptability of wheat production in different climatic zones of Pakistan under climate change scenarios. *Climatic Change*, **94**, 123-142.

Sun, C., H. Cao, H. Shao, X. Lei, and Y. Xiao, 2011: Growth and physiological responses to water and nutrient stress in oil palm. *Journal of Biotechnology*, **10**, 10465-10471.

Supit, I., C.A. van Diepen, A.J.W. de Wit, P. Kabat, B. Baruth, and F. Ludwig, 2010: Recent changes in the climate yield potential of various crops in Europe. *Agricultural Systems*, **103**, 683-694.

Tabachnick, W.J., 2010: Challenges in predicting climate and environmental effects on vector-borne disease episystems in a changing world. *Journal of Experimental Biology*, **213**, 946-954.

Tan, Z., L.L. Tieszen, S. Liu, and E. Tachie-Obeng, 2010: Modeling to evaluate the response of savanna-derived cropland to warming-drying stress and nitrogen fertilizers. *Climatic Change*, **100**, 703-715.

Tao, F. and Z. Zhang, 2010: Adaptation of maize production to climate change in North China Plain: quantify the relative contributions of adaptation options. *European Journal of Agronomy*, **33(3)**, 103-116.

Tao, F. and Z. Zhang, 2011a: Climate change, wheat productivity and water use in the North China Plain: a new super-ensemble-based probabilistic projection. *Agricultural and Forest Meteorology*, **170**, 146-165.

Tao, F. and Z. Zhang, 2011b: Impacts of climate change as a function of global mean temperature: maize productivity and water use in China. *Climatic Change*, **105**, 409-432.

Tao, F. and Z. Zhang, 2013: Climate change, high-temperature stress, rice productivity, and water use in Eastern China: a new superensemble-based probabilistic projection. *Journal of Applied Meteorology and Climatology*, **52(3)**, 531-551.

Tao, F., M. Yokozawa, Y. Xu, Y. Hayashi, and Z. Zhang, 2006: Climate changes and trends in phenology and yields of field crops in China, 1981-2000. *Agriculture and Forest Meteorology*, **138**, 82-92.

Tao, F., M. Yokozawa, J. Liu, and Z. Zhang, 2008a: Climate-crop yield relationships at provincial scales in China and the impacts of recent climate trends. *Climate Research*, **38**, 83-94.

Tao, F., Y. Hayashi, Z. Zhang, T. Sakamoto, and M. Yokozawa, 2008b: Global warming, rice production, and water use in China: developing a probabilistic assessment. *Agricultural and Forest Meteorology*, **148(1)**, 94-110.

Tao, F., Z. Zhang, J. Liu, and M. Yokozawa, 2009a: Modelling the impacts of weather and climate variability on crop productivity over a large area: a new process-based model development, optimization, and uncertainties analysis. *Agriculture and Forest Meteorology*, **149**, 831-850.

Tao, F., Z. Zhang, J. Liu, and M. Yokozawa, 2009b: Modelling the impacts of weather and climate variability on crop productivity over a large area: a new super-ensemble-based probabilistic projection. *Agricultural and Forest Meteorology*, **149**, 1266-1278.

Tao, F., Z. Zhang, and M. Yokozawa, 2011: Dangerous levels of climate change for agricultural production in China. *Regional Environmental Change*, **11(Suppl. 1)**, S41–S48, doi:10.1007/s10113-010-0159-8.

Tao, F., Z. Zhang, S. Zhang, Z. Zhu, and W. Shi, 2012: Response of crop yields to climate trends since 1980 in China. *Climate Research*, **54**, 233-247.

Taub, D.R., B. Miller, and H. Allen, 2008: Effect of elevated CO_2 on the protein concentration of food crops: a meta-analysis. *Global Change Biology*, **14**, 565-575.

Tausz, M., S. Tausz-Posch, R.M. Norton, G.J. Fitzgerald, M.E. Nicolas, and S. Seneweera, 2011: Understanding crop physiology to select breeding targets and improve crop management under increasing atmospheric CO_2 concentrations. *Environmental and Experimental Botany*, **88**, 71-80.

Tchebakova, N., E. Parfenova, G. Lysanova, and A. Soja, 2011: Agroclimatic potential across Central Siberia in an altered twenty-first century. *Environmental Research Letters*, **6(4)**, 045207, doi:10.1088/1748-9326/6/4/045207.

Teixeira, E., G. Fischer, H. van Velthuizen, R. van Dingenen, F. Dentener, G. Mills, C. Walter, and F. Ewert, 2011: Limited potential of crop management for mitigating surface ozone impacts on global food supply. *Atmospheric Environment*, **45**, 2569-2576.

Teixeira, E., G. Fischer, H. van Velthuizen, C. Walter, and F. Ewert, 2013: Global hot-spots of heat stress on agricultural crops due to climate change. *Agricultural and Forest Meteorology*, **170**, 206-215.

Thenkabail, P., J.G. Lyon, H. Turral, and C. Biradar (eds.), 2009: *Remote Sensing of Global Croplands for Food Security*. CRC Press, Boca Raton, FL, USA, 476 pp.

Thomas, R.J., 2008: Opportunities to reduce the vulnerability of dryland farmers in Central and West Asia and North Africa to climate change. *Agriculture, Ecosystems & Environment*, **126**, 36-45.

Thomson, A.M., N.J. Rosenberg, R.C. Izaurralde, and R.A. Brown, 2005: Climate change impacts for the conterminous USA: an integrated assessment. Part 5. Irrigated agriculture and national grain crop production. *Climatic Change*, **69**, 89-105.

Thornton, P.K., J. van de Steeg, A. Notenbaert, and M.K. Herrero, 2009a: Impact of climate change on livestock and livestock systems in developing countries: a review of what we know and what we need to know. *Agricultural Systems*, **101**, 113-127.

Thornton, P.K., P.G. Jones, G. Alagarswamy, and J. Andresen, 2009b: Spatial variation of crop yield response to climate change in East Africa. *Global Environmental Change*, **19**, 54-65.

Thornton, P.K., P.G. Jones, G. Alagarswamy, J. Andresen, and M. Herrero, 2010: Adapting to climate change: agricultural system and household impacts in East Africa. *Agricultural Systems*, **103**, 73-82.

Thornton, P.K., P.G. Jones, P.J. Ericksen, and A.J. Challinor, 2011: Agriculture and food systems in sub-Saharan Africa in a 4°C+ world. *Philosophical Transactions of the Royal Society A*, **369**, 1934, 117-136, doi:10.1098/rsta.2010.0246.

Tianhong, Z., S. Yi, H. Guohong, W. Yan, and S. Bei, 2005: Respective and interactive effects of doubled CO_2 and O_3 concentration on membrane lipid peroxidation and anti-oxidative ability of soybean. *Science in China Series C: Life Sciences*, **48(1)**, 136-141.

Tingem, M., M. Rivington, G. Bellocchi, S. Azam-Ali, and J. Colls, 2008: Effects of climate change on crop production in Cameroon. *Climate Research*, **36**, 65-77.

Tingem, M. and M. Rivington, 2009: Adaptation for crop agriculture to climate change in Cameroon: turning on the heat. *Mitigation and Adaptation Strategies for Global Change*, **14**, 153-168.

Travasso, M., G. Magrin, G. Rodríguez, S. Solman, and M. Núñez, 2009: Climate change impacts on regional maize yields and possible adaptation measures in Argentina. *International Journal of Global Warming*, **1**, 201-213.

Trnka, M., J.E. Olesen, K.C. Kersebaum, A.O. Skjelvåg, J. Eitzinger, B. Seguin, P. Peltonen-Sainio, R. Rötter, A. Iglesias, S. Orlandini, M. Dubrovsky, P. Hlavinka, J. Balek, H. Eckersten, E. Cloppet, P. Calanca, A. Gobin, V. Vucetic, P. Nejedlik, S. Kumar, B. Lalic, A. Mestrea, F. Rossi, J. Kozyra, V. Alexandrov, D. Semerádová, and Z. Zalud, 2011: Agroclimatic conditions in Europe under climate change. *Global Change Biology*, **17**, 2298-2318.

Tubiello, F.N., M. Donatelli, C. Rosenzweig, and C.O. Stockle, 2000: Effects of climate change and elevated CO_2 on cropping systems: model predictions at two Italian locations. *European Journal of Agronomy*, **13(2-3)**, 179-189.

Turner, N. and H. Clifton, 2009: 'It's so different today': climate change and indigenous lifeways in British Colombia, Canada. *Global Environmental Change*, **19**, 180-190.

Twomlow, S., F. Mugabe, M. Mwale, R. Delve, D. Nanja, P. Carberry, and M. Howden, 2008: Building adaptive capacity to cope with increasing vulnerability due to climatic change in Africa – a new approach. *Physics and Chemistry of the Earth*, **33**, 780-787.

UN ECLAC, 2010: *Economics of Climate Change in Latin America and the Caribbean: Summary 2010*. United Nations, Economic Commission for Latin America and the Caribbean (UN ECLAC), Santiago, Chile, 107 pp.

Urban, D., M.J. Roberts, W. Schlenker, and D. Lobell, 2012: Projected temperature changes indicate significant increase in interannual variability of U.S. maize yields. *Climatic Change*, **112**, 525-533.

Van de Geisen, N., J. Liebe, and G. Jung, 2010: Adapting to climate change in the Volta Basin, West Africa. *Current Science*, **98,** 1033-1037.

Van Dingenen, R., F.J. Dentener, F. Raes, M.C. Krol, L. Emberson, and J. Cofala, 2009: The global impact of ozone on agricultural crop yields under current and future air quality legislation. *Atmospheric Environment*, **43**, 604-618.

Vandermeiren, K., H. Harmens, G. Mills, and L. De Temmerman, 2009: Impacts of ground-level ozone on crop production in changing climate. In: *Climate Change and Crops* [Singh, S.N. (ed.)]. Environmental Science and Engineering, Subseries: Environmental Science, Springer-Verlag Berlin Heidelberg, Germany, pp. 213-243.

Van Oort, P.A.J., B. G. H. Timmermans and A.C.P.M. van Swaaij, 2012: Why farmers' sowing dates hardly change when temperature rises. *European Journal of Agronomy*, **40**, 102-111.

Vass, K.K., M.K. Das, P.K. Srivastava, and S. Dey, 2009: Assessing the impact of climate change on inland fisheries in River Ganga and its plains in India. *Aquatic Ecosystem Health & Management*, **12**, 138-151.

Verchot, L.V., M.V. Noordwijk, S. Kandji, T. Tomich, C. Ong, A. Albrecht, J. Mackensen, C. Bantilan, K.V. Anupama, and C. Palm, 2007: Climate change: linking adaptation and mitigation through agroforestry. *Mitigation and Adaptation Strategies for Global Change,* **12**, 901-918.

Vermeulen, S.J., B. Campbell, and J. Ingram, 2012: Climate change and food systems. *Annual Review of Environment and Resources*, **37**, 195-222.

Vitali, A., M. Segnalini, L. Bertocchi, U. Bernabucci, A. Nardone, and N. Lacetera, 2009: Seasonal pattern of mortality and relationships between mortality and temperature-humidity index in dairy cows. *Journal of Dairy Science*, **92(8)**, 3781-3790.

von Braun, J. and M. Torero, 2009: Exploring the price spike. *Choices*, **24**, 16-21.

Walker, N.J. and R.E. Schulze, 2008: Climate change impacts on agro-ecosystem sustainability across three climate regions in the maize belt of South Africa. *Agriculture, Ecosystems, and Environment*, **124**, 114-124.

Wall E, A. Wreford, K. Topp, and D. Moran, 2010: Biological and economic consequences heat stress due to a changing climate on UK livestock. *Advances in Animal Biosciences*, **1(1)**, 53.

Walter, L., T. Streck, H. Rosa, and C. Kruger, 2010: Climate change and its effects on rice. *Ciencia Rural*, **40**, 2411-2418.

Wang, H.L., Y.T. Gan, R.Y. Wang, J.Y. Niu, H. Zhao, Q.G. Yang, and G.C. Li, 2008: Phenological trends in winter wheat and spring cotton in response to climate changes in northwest China. *Agricultural and Forest Meteorology*, **148**, 1242-1251.

Wang, M., Y. Li, W. Ye, J. Bornman, and X. Yan, 2011: Effects of climate change on maize production, and potential adaptation measures: a case study in Jilin Province, China. *Climate Research*, **46**, 223-242.

Wang, X., W. Manning, Z. Feng, and Y. Zhu, 2007: Ground-level ozone in China: distribution and effects on crop yields. *Environmental Pollution*, **147**, 394-400.

Wassmann, R., S.V.K. Jagadish, S. Heur, A. Ismail, E. Redona, R. Serraj, R.K. Singh, G. Howell, H. Pathak, and K. Sumfleth, 2009: Climate change affecting rice production: the physiological and agronomic basis for possible adaptation strategies. In: *Advances in Agronomy, Vol. 101* [Sparks, D.L. (ed.)]. Elsevier Science and Technology/Academic Press, Waltham, MA, USA, pp. 59-122.

Watson, J. and A. Challinor, 2013: The relative importance of rainfall, temperature and yield data for a regional-scale crop model. *Agricultural and Forest Meteorology*, **170**, 47-57.

Weatherhead, E., S. Gearheard, and R. Barry, 2010: Changes in weather persistence: Insight from Inuit knowledge. *Global Environmental Change*, **20(3)**, 523-528.

Webb, L.B., P.H. Whetton, and E.W.R. Barlow, 2011: Observed trends in winegrape maturity in Australia. *Global Change Biology*, **17**, 2707-2719.

Welch, J.R., J.R. Vincent, M. Auffhammer, P.F. Moya, A. Dobermann, and D. Dawe, 2010: Rice yields in tropical/subtropical Asia exhibit large but opposing sensitivities to minimum and maximum temperatures. *Proceedings of the National Academy of Sciences of the United States of America*, **107(33)**, 14562-14567, doi:10.1073/pnas.1001222107.

White, A., P. Whalen, and G.V. Jones, 2009: Land and wine. *Nature Geoscience*, **2(2)**, 82-84.

Wijeratne, M.A., A. Anandacoomaraswamy, M.K.S.L.D. Amarathunga, J. Ratnasiri, B.R.S.B. Basnayake, and N. Kalra, 2007: Assessment of impact of climate change on productivity of tea (*Camellia sinensis* L.) plantations in Sri Lanka. *Journal of the National Science Foundation of Sri Lanka*, **35(2)**, 119-126.

Wilson, S.K., N.J. Graham, M.S. Pratchett, G.P. Jones, and V.C. Polunin, 2006: Multiple disturbances and the global degradation of coral reefs: are reef fishes at risk or resilient? *Global Change Biology*, **12**, 2220-2234.

Winters P., R. Murgai, E. Sadoulet, A.D. Janvry, and G. Frisvold, 1998: Economic and welfare impacts of climate change on developing countries. *Environmental and Resource Economics*, **12**, 1-24.

Wolfe, D.W., L. Ziska, C. Petzoldt, A. Seaman, L. Chase, and K. Hayhoe, 2008: Projected change in climate thresholds in the Northeastern U.S.: implications for crops, pests, livestock, and farmers. *Mitigation and Adaptation Strategies for Global Change*, **13**, 555-575.

World Bank, 2012: *Global Monitoring Report 2012: Food Prices, Nutrition, and the Millenium Development Goals*. Global Monitoring Report (GMR) 68171, The World Bank and the International Monetary Fund, The World Bank, Washington, DC, USA, 169 pp.

Wratt, D., A.B. Mullan, A. Tait, R. Woods, T. Baisden, D. Giltrap, K. Lock, J. Hendy, Suzi Kerr, A. Stroombergen, and A. Stojanovik, 2008: *Costs and Benefits of Climate Change and Adaptation to Climate Change in New Zealand Agriculture: What Do We Know So Far?* Contract Report by Integrated Research on the Economics of climate Change Impacts, Adaptation and Mitigation (Ecoclimate Consortium) for the Ministry of Agriculture and Forestry, Wellington, New Zealand, 121 pp.

Wright, B.D., 2011: The economics of grain price volatility. *Applied Economic Perspectives and Policy*, **33(1)**, 32-58.

Xenopoulus, M.A., D.M. Lodge, J. Alcamo, M. Märker, K. Schulze, and D.P. Van Vuuren, 2005: Scenarios of freshwater fish extinctions from climate change and water withdrawal. *Global Change Biology*, **11**, 1557-1564.

Xiao, G., W. Liu, Q. Xu, Z. Sun, and J. Wang, 2005: Effects of temperature increase and elevated CO_2 concentration, with supplemental irrigation, on the yield of rain-fed spring wheat in a semiarid region of China. *Agricultural Water Management*, **74**, 243-255.

Xiong, W., E. Lin, H. Ju, and Y. Xu, 2007: Climate change and critical thresholds in China's food security. *Climatic Change*, **81**, 205-221.

Xiong, W., D. Conway, E. Lin, and I. Holman, 2009: Potential impacts of climate change and climate variability on China's rice yield and production. *Climate Research*, **40**, 23-35.

Yang, L., Y. Wang, G. Dong, H. Gu, J. Huang, J. Zhu, H. Yang, G. Liu, and Y. Han, 2007: The impact of Free-Air CO_2 Enrichment (FACE) and nitrogen supply on grain quality of rice. *Field Crops Research*, **102**, 128-140.

Yang, P., W. Wu, Z. Li, Q. Yu, M. Inatsu, Z. Liu, P. Tang, Y. Zha, M. Kimoto, and H. Tang, 2013. Simulated impact of elevated CO_2, temperature, and precipitation on the winter wheat yield in the North China Plain. *Regional Environmental Change*, **14(1)**, 61-74.

Yang, X., Z. Liu, and F. Chen, 2013: The possible effect of climate warming on northern limits of cropping system and crop yield in China. *Agricultural Sciences in China*, **10(4)**, 585-594.

Yates, D.N. and K.M. Strzepek, 1998: An assessment of integrated climate change impacts on the agricultural economy of Egypt. *Climatic Change*, **38(3)**, 261-287.

You, L., M. Rosegrant, S. Wood, and D. Sun, 2009: Impact of growing season temperature on wheat productivity in China. *Agricultural and Forest Meteorology*, **149**, 1009-1014.

Zezza, A., B. Davis, C. Azzarri, K. Covarrubias, L. Tasciotti, and G. Angriquez, 2008: *The Impact of Rising Food Prices on the Poor*. ESA Working Paper 08-07, Agricultural Development Economics Division (ESA) of the Food and Agricultural Organization of the United Nations (FAO), Rome, Italy, 37 pp.

Zhang, X. and X. Cai, 2011: Climate change impacts on global agricultural land availability. *Environmental Research Letters*, **6**, 014014, doi:10.1088/1748-9326/6/1/014014.

Zhang, X.-C. and W.Z. Liu, 2005: Simulating potential response of hydrology, soil erosion, and crop productivity to climate change in Changwu tableland region on the Loess Plateau of China. *Agricultural and Forest Meteorology*, **131(3-4)**, 127-142.

Zhang, T., J. Zhu, X. Yang, and X. Zhang, 2008: Correlation changes between rice yields in North and Northwest China and ENSO from 1960 to 2004. *Agricultural and Forest Meteorology*, **148**, 1021-1033.

Zhang, T., J. Zhu, and R. Wassmann, 2010: Responses of rice yields to recent climate change in China: an empirical assessment based on long-term observations at different spatial scales (1981-2005). *Agricultural and Forest Meteorology*, **150**, 1128-1137.

Zhao, Y., C. Wang, S. Wang, and L.V. Tibig, 2005: Impacts of present and future climate variability on agriculture and forestry in the humid and sub-humid tropics. *Climatic Change*, **70**, 73-116.

Zhu, T., C. Ringler, M.M. Iqbal, T.B. Sulser, and M.A. Goheer, 2013: Climate change impacts and adaptation options for water and food in Pakistan: scenario analysis using integrated global water and food production model. *Water International*, **38(5)**, 651-669.

Ziska, L.H., 2010: Global climate change and carbon dioxide: assessing weed biology and management. In: *Handbook of Climate Change and Agro-Ecosystems: Impacts, Adaptation and Mitigation* [Rosenzweig, C. and D. Hillel (eds.)]. World Scientific Publishing, Hackensack, NJ, USA, pp. 191-208.

Ziska, L.H. and E.W. Goins, 2006: Elevated atmospheric carbon dioxide and weed populations in glyphosate treated soybean. *Crop Science*, **46**, 1354-1359.

Ziska, L.H., D. Blumenthal, G. Runion, E. Hunt, and H. Diaz-Soltero, 2011: Invasive species and climate change: an agronomic perspective. *Climatic Change*, **105(1-2)**, 13-42.

Ziska, L.H., J.A. Bunce, H. Shimono, D.R. Gealy, J.T. Baker, P.C.D. Newton, M.P. Reynolds, K.S.V. Jagadish, C. Zhu, M. Howden, and L.T. Wilson, 2012: Food security and climate change: on the potential to adapt global crop production by active selection to rising atmospheric carbon dioxide. *Proceedings of the Royal Society B*, **279**, 4097-4105.

Zougmoré, R., A. Mando, and L. Stroosnijder, 2010: Benefits of integrated soil fertility and water management in semi-arid West Africa: an example study in Burkina Faso. *Nutrient Cycling in Agroecosystems*, **18**, 17-27.

Zumbach, B., I. Misztal, S. Tsuruta, J.P. Sanchez, M. Azain, W. Herring, J. Holl, T. Long, and M. Culbertson, 2008: Genetic components of heat stress in finishing pigs: Development of a heat load function. *Journal of Animal Science*, **86(9)**, 2082-2088.

Zwiers, F.W., X. Zhang, and Y. Feng, 2011: Anthropogenic influence on long return period daily temperature extremes at regional scales. *Journal of Climate*, **24(3)**, 881-892.

8 Urban Areas

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Revi, A., D.E. Satterthwaite, F. Aragón-Durand, J. Corfee-Morlot, R.B.R. Kiunsi, M. Pelling, D.C. Roberts, and W. Solecki, 2014: Urban areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 535-612.

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8

Executive Summary

Urban climate adaptation can build resilience and enable sustainable development. {8.1, 8.2, 8.3}

Action in urban centers is essential to successful global climate change adaptation. Urban areas hold more than half the world's population and most of its built assets and economic activities. They also house a high proportion of the population and economic activities most at risk from climate change, and a high proportion of global greenhouse gas emissions are generated by urban-based activities and residents (*medium confidence*, based on *medium evidence*, *high agreement*). {8.1}

Much of key and emerging global climate risks are concentrated in urban areas. Rapid urbanization and rapid growth of large cities in low- and middle-income countries have been accompanied by the rapid growth of highly vulnerable urban communities living in informal settlements, many of which are on land at high risk from extreme weather (*medium confidence*, based on *medium evidence*, *high agreement*). {8.2, 8.3, Tables 8-2, 8-3}

Cities are composed of complex inter-dependent systems that can be leveraged to support climate change adaptation via effective city governments supported by cooperative multilevel governance. This can enable synergies with infrastructure investment and maintenance, land use management, livelihood creation, and ecosystem services protection (*medium confidence*, based on *limited evidence*, *medium agreement*). {8.3, 8.4}

Urban adaptation action that delivers mitigation co-benefits is a powerful, resource-efficient means to address climate change and to realize sustainable development goals (*medium confidence*, based on *medium evidence*, *high agreement*). {8.4}

Urban climate change risks, vulnerabilities, and impacts are increasing across the world in urban centers of all sizes, economic conditions, and site characteristics. {8.2}

Urban climate change-related risks are increasing (including rising sea levels and storm surges, heat stress, extreme precipitation, inland and coastal flooding, landslides, drought, increased aridity, water scarcity, and air pollution) with widespread negative impacts on people (and their health, livelihoods, and assets) and on local and national economies and ecosystems (*very high confidence*, based on *robust evidence*, *high agreement*). These risks are amplified for those who live in informal settlements and in hazardous areas and either lack essential infrastructure and services or where there is inadequate provision for adaptation. {8.2, Table 8-2}

Climate change will have profound impacts on a broad spectrum of infrastructure systems (water and energy supply, sanitation and drainage, transport and telecommunication), services (including health care and emergency services), the built environment, and ecosystem services. These interact with other social, economic, and environmental stressors exacerbating and compounding risks to individual and household well-being (*medium confidence*, based on *medium evidence*, *high agreement*). {8.2}

Cities and city regions are sufficiently dense and of a spatial scale that they influence their local micro-climate. Climate change will interact with these conditions in a variety of ways, some of which will exacerbate the level of climate risk (*high confidence*, based on *robust evidence*, *high agreement*). {8.2}

Urban climate adaptation provides opportunities for both incremental and transformative development. {8.3, 8.4}

Urban adaptation provides opportunities for incremental and transformative adjustments to development trajectories toward resilience and sustainable development via effective multilevel urban risk governance, alignment of policies and incentives, strengthened local government and community adaptation capacity, synergies with the private sector, and appropriate financing and institutional development. Opportunities to do so are high in many rapidly growing cities where institutions and infrastructure are

being developed, though there is limited evidence of this being realized in practice (*medium confidence*, based on *limited evidence*, *high agreement*). {8.4}

Urban adaptation can enhance economic comparative advantage, reducing risks to enterprises and to households and communities (*medium confidence*, based on *medium evidence*, *high agreement*). {8.3}

City-based disaster risk management with a central focus on risk reduction is a strong foundation on which to address increasing exposure and vulnerability and thus to build adaptation. Closer integration of disaster risk management and climate change adaptation along with the incorporation of both into local, subnational, national, and international development policies can provide benefits at all scales (*high confidence*, based on *medium evidence*, *high agreement*). {8.3}

Ecosystem-based adaptation is a key contributor to urban resilience (*medium confidence*, based on *medium evidence*, *high agreement* (among practitioners)). {8. 3}

Effective urban food-security related adaptation measures (especially social safety nets but also including urban and peri-urban agriculture, local markets, and green roofs) can reduce climate vulnerability especially for low-income urban dwellers (*medium confidence*, based on *medium evidence*, *medium agreement*). {8.3}

Good quality, affordable, well-located housing provides a strong base for city-wide climate change adaptation minimizing current exposure and loss. Possibilities for building stock adaptation rest with owners and public, private, and civil society organizations (*high confidence*, based on *robust evidence*, *high agreement*). {8.3, 8.4}

Reducing basic service deficits and building resilient infrastructure systems (water supply, sanitation, storm and waste water drains, electricity, transport and telecommunications, health care, education, and emergency response) can significantly reduce hazard exposure and vulnerability to climate change, especially for those who are most at risk or vulnerable (*very high confidence*, based on *robust evidence*, *high agreement*). {8.3}

For most key climate change associated hazards in urban areas, risk levels increase from the present (with current adaptation) to the near term but high adaptation can reduce these risk levels significantly. It is less able to do so for the longer term, especially under a global mean temperature increase of 4°C. {Tables 8-3, 8-6}

Implementing effective urban adaptation is possible and can be accelerated. {8.4}

Urban governments are at the heart of successful urban climate adaptation because so much adaptation depends on local assessments and integrating adaptation into local investments, policies, and regulatory frameworks (*high confidence*). {8.4}

Well governed cities with universal provision of infrastructure and services have a strong base for building climate resilience if processes of planning, design, and allocation of human capital and material resources are responsive to emerging climate risks (*medium confidence*, based on *medium evidence*, *high agreement*). {8.4}

Building human and institutional capacity for adaptation in local governments, including scope for reflecting on incremental and transformative adaptation pathways, accelerates implementation and improves urban adaptation outcomes (*high confidence*, based on *medium evidence*, *high agreement*). {8.4}

Coordinated support from higher levels of governments, the private sector, and civil society and horizontal learning through networks of cities and practitioners benefits urban adaptation (*medium confidence*, based on *medium evidence*, *medium agreement*). {8.4}

Leadership within local governments and also across all scales is important in driving successful adaptation and in promoting and sustaining a broad base of support for the urban adaptation agenda (*medium confidence*, based on *medium evidence*, *high agreement*). {8.4}

Addressing political interests, mobilizing institutional support for climate adaptation, and ensuring voice and influence to those most at risk are important strategic adaptation concerns (*medium confidence*, based on *limited evidence*, *medium agreement*). {8.4}

Enabling the capacity of low-income groups and vulnerable communities, and their partnership with local governments, can be an effective urban adaptation strategy (*medium confidence*, based on *limited evidence*, *high agreement*). {8.3, 8.4}

Urban centers around the world face severe constraints to raising and allocating resources to implement adaptation. In most low- and middle-income country cities, infrastructure backlogs, lack of appropriate mandates, and lack of financial and human resources severely constrain adaptation action. Small urban centers often lack economies of scale for adaptation investments and local capacity to act, as they have relatively low national and international profiles (*medium confidence*, based on *medium evidence*, *high agreement*). {8.3, 8.4}

International financial institutions provide limited financial support for adaptation in urban areas. There is limited current commitment to finance urban adaptation from different levels of government and international agencies (*medium confidence*, based on *limited evidence*, *high agreement*). {8.4}

A scientific evidence base in each urban center is essential for effective adaptation action. This includes local risk and vulnerability assessments and information and data with which to consider current and future risk and adaptation and development options (*medium confidence*, based on *medium evidence*, *high agreement*). {8.4}

Dealing with the uncertainty associated with climate change projections and balancing them with actions to address current vulnerabilities and adaptation costs helps to assist implementation in urban areas (*medium confidence*, based on *medium evidence*, *medium agreement*). {8.2, 8.4}

8.1. Introduction

8.1.1. Key Issues

Adaptation to climate change depends centrally on what is done in urban centers, which now house more than half the world's population and concentrate most of its assets and economic activities (World Bank, 2008; UN DESA Population Division, 2012). As Section 8.4 emphasizes, this will require responses by all levels of government as well as individuals and communities, the private sector, and civil society. The serious impacts of extreme weather on many urban centers each year demonstrate some of the risks and vulnerabilities to be addressed (UNISDR, 2009; IFRC, 2010). Climate change will usually add to these and other risks and vulnerabilities. Urban policies also have major implications for mitigation, especially for future levels of greenhouse gas (GHG) emissions and for delivering co-benefits, as discussed in WGIII AR5. This chapter focuses on the possibilities for governments, enterprises, and populations to adapt urban centers to the direct and indirect impacts of climate change.

The level of funding needed for sound urban adaptation could exceed the capacities of local and national governments and international agencies (Parry et al., 2009; Brugmann, 2012). Much of the investment will have to come from individuals and households, communities, and firms through their decisions to address adaptation and resilience (Agrawala and Fankhauser, 2008; Fankhauser and Soare, 2013). This might suggest little role for governments, especially local governments. But whether these small-scale decisions by households, communities, and firms do contribute to adaptation depends in large part on what local governments do, encourage, support, and prevent—as well as their contribution to providing required infrastructure and services. An important part of this is the provision by local governments of appropriate regulatory frameworks and the application of building standards, to ensure that the choices made by individuals, households, and firms support adaptation and prevent maladaptation. For instance, land use planning and management have important roles in ensuring sufficient land for housing that avoids dangerous sites and protects key ecological services and systems (UN-HABITAT, 2011a).

In reviewing adaptation needs and options for urban areas, the documentation reviewed for this chapter points to two key conclusions. The first is how much the adaptive capacity of any city depends on the quality of provision and coverage of infrastructure and services; the capacities for investments and land use management; and the degree to which buildings and infrastructure meet health and safety standards. This capacity provides a foundation for city resilience on which adaptation can be built. There is little of this foundation in most urban centers in low-income and in many middle-income nations. The second conclusion is the importance of city and municipal governments acting now to incorporate climate change adaptation into their development plans and policies and infrastructure investments. This includes not only building that foundation of resilience (and its institutional, governance, and financial underpinnings) but also mobilizing new resources, adjusting building and land use regulations, and continuously developing the local capacity to respond. This is not to diminish the key roles of other actors. But it will fall to city and municipal government to provide the scaffolding and regulatory framework within which other stakeholders contribute and collaborate. Thus, adaptation in urban areas depends on the competence and capacity of local governments and a locally rooted iterative process of learning about changing risks and opportunities, identifying and evaluating options, making decisions, and revising strategies in collaboration with a range of actors.

8.1.2. Scope of the Chapter

This chapter focuses on what we know about the potential impact of climate change on urban centers and their populations and enterprises (Section 8.2), what measures are being taken to adapt to these changes (and protect vulnerable groups) (Section 8.3), and what institutional and governance changes can underpin adaptation (Section 8.4). Both this and Chapter 9 highlight the multiple linkages between rural and urban areas that have relevance for adaptation. This chapter also overlaps with Chapter 10, especially in regard to infrastructure, although this chapter focuses on urban infrastructure and in particular the infrastructure that comes within the responsibilities or jurisdiction of urban governments.

This chapter draws its urban statistics from the United Nations Population Division (UN DESA Population Division, 2012). Urban centers vary from those with a few thousand (or in some nations a few hundred) inhabitants to metropolitan areas with more than 20 million inhabitants. There is no international agreement—and considerable national variation—in how urban areas are defined (UN DESA Population Division, 2012). The main differences are in how settlements with a few hundred up to 20,000 inhabitants are classified; depending on the country, some, most, or all of these may be classified as urban or rural. There are also differences in how urban boundaries are set. In some places, they encompass the urban built up area or the central urban core; in others, they go well beyond the built up area and include large areas devoted to agriculture (Satterthwaite, 2007).

The issue here is whether provision for adaptation includes "rural" populations living around urban centers and within urban jurisdictions. In addition, it is common for part of the workforce in larger urban centers to live outside the urban center and to commute—and this may include many that live in settlements designated as rural. There is also no agreed definition for what constitutes a city—although the term city implies an urban center with some economic, political, or cultural importance and would not be applied to most small urban centers.

8.1.3. Context: An Urbanizing World

In 2008, for the first time, more than half the world's population was living in urban centers and the proportion continues to grow (UN DESA Population Division, 2012). Three-quarters of the world's urban population and most of its largest cities are now in low- and middle-income nations. A comparison of Figures 8-1 and 8-2 highlights the increase in the number of large cities from 1950 to what is projected for 2025. UN projections suggest that almost all the increase in the world's population up to 2050 will be in urban centers in what are currently low- and middle-income nations (see Table 8-1). Most of the gross domestic product (GDP) of most nations and globally is generated

in urban centers and most new investments have concentrated there (World Bank, 2008; Satterthwaite et al., 2010). Clearly, just in terms of the population, economic activities, assets, and climate risk they increasingly concentrate, adapting urban areas to climate change requires serious attention.

Most urbanization is underpinned by an economic logic. All wealthy nations are predominantly urbanized and rapid urbanization in low- and middle-income nations is usually associated with rapid economic growth (World Bank, 2008; Satterthwaite et al., 2010). Most of the world's largest cities are in its largest economies (World Bank, 2008;

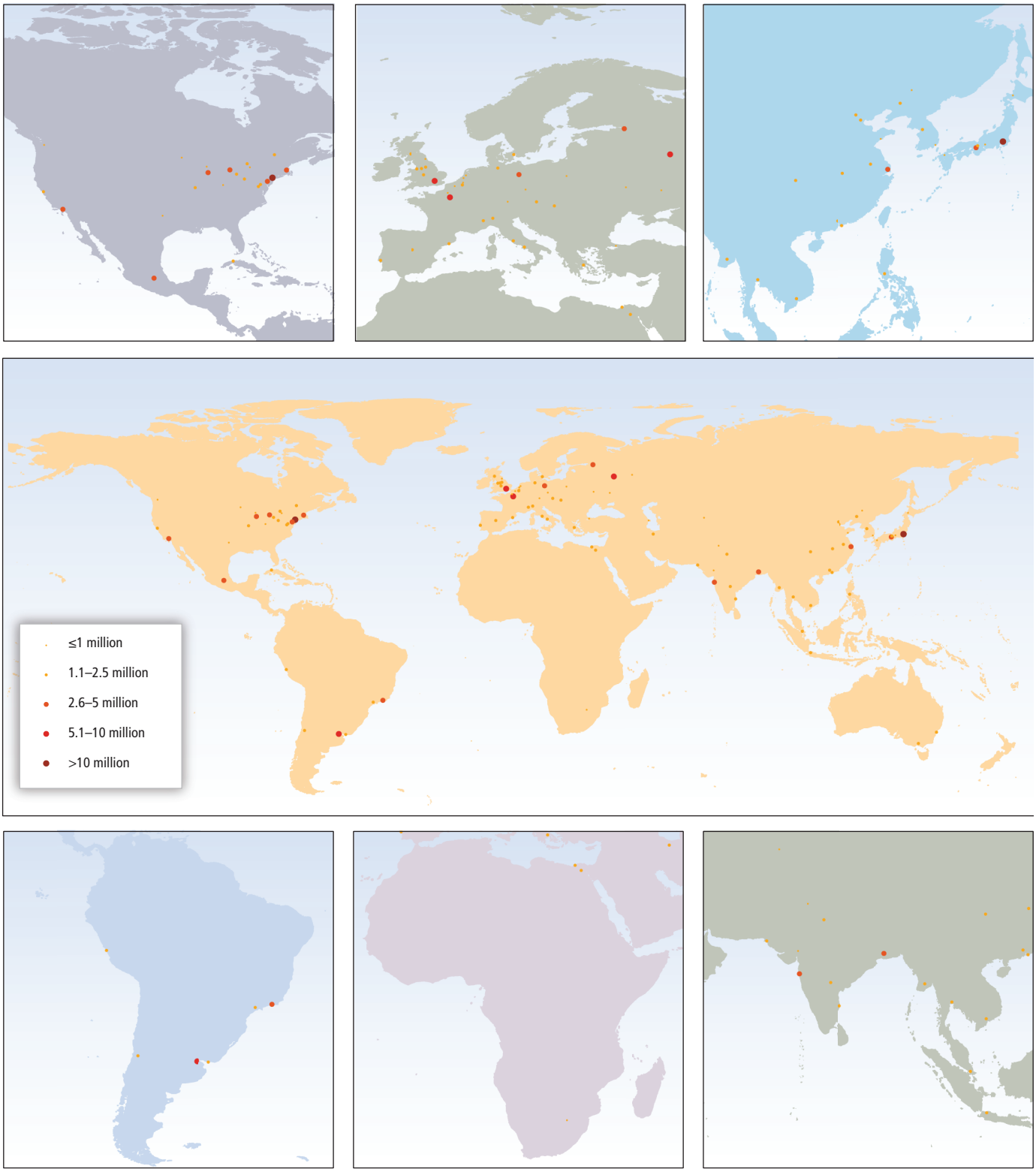


Figure 8-1 | Global and regional maps showing the location of urban agglomerations with 750,000-plus inhabitants in 1950 (derived from statistics in UN DESA Population Division, 2012).

Satterthwaite et al., 2010). If rapid urbanization and rapid city population growth are associated with economic success, it suggests that more resources should be available there to support adaptation. But, as discussed in Section 8.3, this is rarely the case. In most urban centers in low- and middle-income nations including many successful cities, local governments have been unable to manage their economic and physical expansion and there are large deficits in provision for infrastructure and services that are relevant to climate change adaptation. About one in seven people in the world live in poor quality, overcrowded accommodation in urban areas with inadequate provision (or none) for basic infrastructure

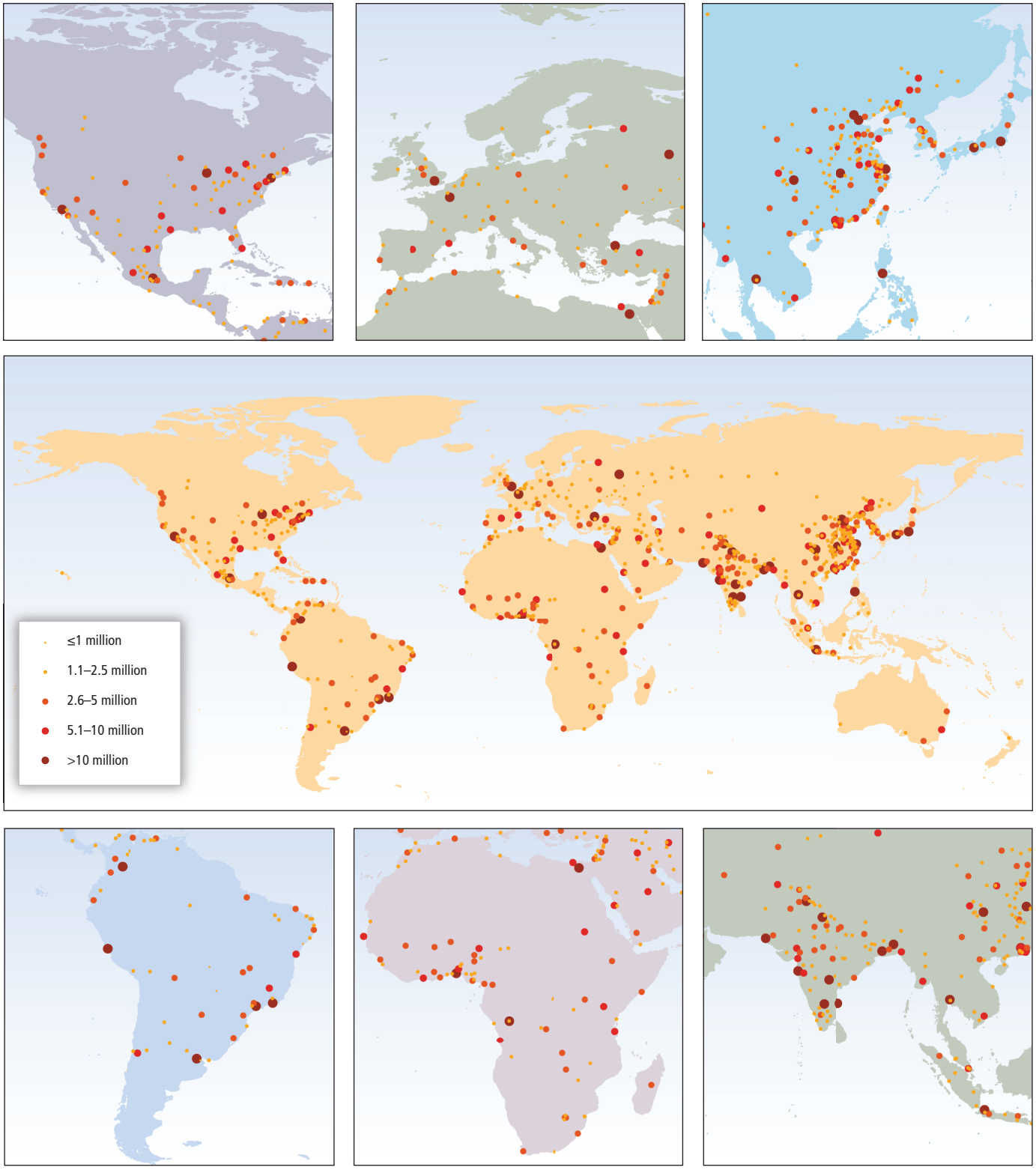


Figure 8-2 | Global and regional maps showing the location of urban agglomerations with 750,000-plus inhabitants projected for 2025 (derived from statistics in UN DESA Population Division, 2012).

Table 8-1 | Distribution of the world's urban population by region, 1950–2010 with projections to 2030 and 2050. Source: Derived from statistics in United Nations (2012).

	Major area, region, or country	1950	1970	1990	2010	Projected for 2030	Projected for 2050
Urban population (millions of inhabitants)	**World**	745	1352	2281	3559	4984	6252
	More developed regions	442	671	827	957	1064	1127
	Less developed regions	304	682	1454	2601	3920	5125
	Least developed countries	15	41	107	234	477	860
	Sub-Saharan Africa	20	56	139	298	596	1069
	Northern Africa	13	31	64	102	149	196
	Asia	245	506	1032	1848	2703	3310
	China	65	142	303	660	958	1002
	India	63	109	223	379	606	875
	Europe	281	412	503	537	573	591
	Latin America and the Caribbean[a]	69	163	312	465	585	650
	Northern America	110	171	212	282	344	396
	Oceania	8	14	19	26	34	40
Percent of the population in urban areas	**World**	29.4	36.6	43.0	51.6	59.9	67.2
	More developed regions	54.5	66.6	72.3	77.5	82.1	85.9
	Less developed regions	17.6	25.3	34.9	46.0	55.8	64.1
	Least developed countries	7.4	13.0	21.0	28.1	38.0	49.8
	Sub-Saharan Africa	11.2	19.5	28.2	36.3	45.7	56.5
	Northern Africa	25.8	37.2	45.6	51.2	57.5	65.3
	Asia	17.5	23.7	32.3	44.4	55.5	64.4
	China	11.8	17.4	26.4	49.2	68.7	77.3
	India	17.0	19.8	25.5	30.9	39.8	51.7
	Europe	51.3	62.8	69.8	72.7	77.4	82.2
	Latin America and the Caribbean	41.4	57.1	70.3	78.8	83.4	86.6
	Northern America	63.9	73.8	75.4	82.0	85.8	88.6
	Oceania	62.4	71.2	70.7	70.7	71.4	73.0
Percent of the world's urban population	**World**	100.0	100.0	100.0	100.0	100.0	100.0
	More developed regions	59.3	49.6	36.3	26.9	21.4	18.0
	Less developed regions	40.7	50.4	63.7	73.1	78.6	82.0
	Least developed countries	2.0	3.0	4.7	6.6	9.6	13.8
	Sub-Saharan Africa	2.7	4.1	6.1	8.4	11.9	17.1
	Northern Africa	1.7	2.3	2.8	2.9	3.0	3.1
	Asia	32.9	37.4	45.2	51.9	54.2	52.9
	China	8.7	10.5	13.3	18.6	19.2	16.0
	India	8.5	8.1	9.8	10.6	12.2	14.0
	Europe	37.6	30.5	22.0	15.1	11.5	9.5
	Latin America and the Caribbean	9.3	12.1	13.7	13.1	11.7	10.4
	Northern America	14.7	12.6	9.3	7.9	6.9	6.3
	Oceania	1.1	1.0	0.8	0.7	0.7	0.6

[a]Chapter 26 on North America includes Mexico; in the above statistics, Mexico is included in Latin America and the Caribbean.

and services, mostly in informal settlements (UN-HABITAT, 2003a; Mitlin and Satterthwaite, 2013). Much of the health risk and vulnerability to climate change is concentrated in these settlements (Mitlin and Satterthwaite, 2013). So this chapter is concerned not only with an adaptation deficit for, but also with a development deficit that is relevant to, this risk and vulnerability.

Many aspects of urban change in recent decades have been so rapid that they have overwhelmed government capacity to manage them. Among the 611 cities with more than 750,000 inhabitants in 2010, 47 had populations that had grown more than 20-fold since 1960; in 120, the growth was more than 10-fold (statistics in this paragraph are drawn from data in UN DESA Population Division, 2012). The increasing concentration of the world's urban population and its largest cities outside the highest income nations represents an important change. Over the 19th and 20th centuries, most of the world's urban population and most of its largest cities were in its most prosperous nations. Now, urban areas in low- and middle-income nations have close to two-fifths

of the world's total population, close to three-quarters of its urban population, and most of its large cities. In 2011, of the 23 "mega-cities" (with populations over 10 million), only 5 were in high-income nations (two in Japan, two in the USA, one in France). Of the remaining 18, 4 were in China, 3 in India, and 2 in Brazil. But more than three-fifths of the world's urban population is in urban centers with fewer than 1 million inhabitants and it is here that much of the growth in urban population is occurring.

Underlying these population statistics are large and complex economic, social, political, and demographic changes, including the multiplication in the size of the world's economy and the shift in economic activities and employment structures from agriculture to industry and services (and within services to information production and exchange) (Satterthwaite, 2007). One of the most significant changes has been the growth in the size and importance of cities whose economies increased and changed as a result of globalization (Sassen, 2012). Another is the number of large cities that are now centers of large extended metropolitan regions.

One of the challenges for this chapter is to convey the very large differences in adaptive capacity between urban centers. There are tens of thousands of urban centers worldwide with very large and measurable differences in population, area, economic output, human development, quality, and coverage of infrastructure and services, ecological footprint, and GHG emissions. The differences in adaptive capacity are far less easy to quantify. Table 8-2 illustrates differences in adaptive capacity and factors that influence it. It indicates how each urban center falls within a spectrum in at least four key factors that influence adaptation: local government capacity; the proportion of residents served with risk-reducing infrastructure and services; the proportion living in housing built to appropriate health and safety standards; and the levels of risk from climate change's direct and indirect impacts. This chapter and Table 8-2 also draw on detailed case studies to illustrate this diversity—New York (Solecki, 2012), Durban (Roberts and O'Donoghue, 2013), and Dar es Salaam (Kiunsi, 2013). Section 8.5 provides tables of current and indicative future climate risks for Dar es Salaam, Durban, London, and New York.

Many attributes of urban centers can be measured and compared. As noted above, populations vary from a few hundred to more than 20 million. Areas vary from less than one to thousands of square kilometers. Average life expectancy at birth varies from more than 80 years to less than 40 years, and under-five mortality rates vary by a factor of 20 or more (Mitlin and Satterthwaite, 2013). Average per capita incomes vary by a factor of at least 300; so too does the funding available to local governments per person (UCLG, 2010). GHG emissions per person (in tonnes of carbon dioxide equivalent) vary by more than 100 (Dodman, 2009; Hoornweg et al., 2011).

There are large differences between urban centers in the extent to which their economies are dependent on climate-sensitive resources (including commercial agriculture, water, and tourism).There are also large variations in the scale and nature of impacts from extreme weather. As Table 8-2 suggests, there are urban indicators relevant for assessing the resilience to climate change impacts that urban areas have acquired (including the proportion of the population with water piped to their homes, sewers, drains, health care, and emergency services); it is more of a challenge to find indicators for the climate change related risks and for the quality and capacity of government.

Recent analyses of disaster impacts show that a high proportion of the world's population most affected by extreme weather events is concentrated in urban centers (UNISDR, 2009, 2011; IFRC, 2010). As shown in Table 8-2, a high proportion of these urban centers lack both local governments with the capacity to reduce disaster risk, and much of the necessary infrastructure. Their low-income households may require particular assistance because of greater exposure to hazards, lower adaptive capacity, more limited access to infrastructure or insurance, and fewer possibilities to relocate to safer accommodation, compared to wealthier residents.

All successful urban centers have had to adapt to environmental conditions and available resources, although local resource constraints have often been overcome by drawing on resources and using sinks from "distant elsewhere" (Rees, 1992; McGranahan, 2007); this includes importing goods that are resource intensive and whose fabrication involves large GHG emissions. The growth of urban population over the last century has also caused a very large anthropogenic transformation of terrestrial biomes. Urban centers cover only a small proportion of the world's land surface—according to Schneider et al. (2009) only 0.51% of the total land area; only in Western Europe do they cover more than 1%. However, their physical and ecological footprints are much larger. The net ecological impact of urban centers includes the decline in the share of wild and semi-natural areas from about 70% to less than 50% of land area, largely to accommodate crop and pastoral land to support human consumption (Ellis et al., 2010). It has led not only to a decrease in biodiversity but to fragmentation in much of the remaining natural areas and a threat to the ecological services that support both rural and urban areas. Future projections (Seto et al., 2012) suggest that, if current trends continue, urban land cover will increase by 1.2 million km^2 by 2030, nearly tripling global urban land area between 2000 and 2030. This would mean a "considerable loss of habitats in key biodiversity hotspots," destroying the green infrastructure that is key in helping areas adapt to climate change impacts (Seto et al., 2012, p. 16083) as well as increasing the exposure of population and assets to higher risk levels.

Many of the challenges and opportunities for urban adaptation relate to the central features of city life—the concentration of people, buildings, economic activities, and social and cultural institutions (Romero-Lankao and Dodman, 2011). Agglomeration economies are usually discussed in relation to the advantages for enterprises locating in a particular city. But the concentrations of people, enterprises, and institutions in urban areas also provide potential agglomeration economies in lower unit costs for piped water, sewers, drains, and a range of services (solid waste collection, schools, health care, emergency services, policing) and in the greater capacity for people, communities, and institutions to respond collectively (Hardoy et al., 2001). At the same time, the advantages that come with these concentrations of people and activities are also accompanied by particular challenges—for instance, the management of storm and surface runoff and measures to reduce heat islands. Large cities concentrate demand and the need for ecological services and natural resources (water, food, and biomass), energy, and electricity, and many city enterprises rely on lifeline infrastructure and supply chains that can be disrupted by climate change (UNISDR, 2013; see also Section 8.3.3).

Table 8-2 | The large spectrum in the capacity of urban centers to adapt to climate change. One of the challenges for this chapter is to convey the very large differences in adaptive capacity between urban centers. This table seeks to illustrate differences in adaptive capacity and the factors that influence it. For a more detailed assessment of adaptation potentials and challenges for specific cities (Dar es Salaam, Durban, London, and New York), see Table 8-6. Sources: This table was constructed to provide a synthesis of key issues, so it draws on all the sources cited in this chapter. However, it draws in particular on Solecki (2012), Kiunsi (2013), and Roberts and O'Donoghue (2013).

Indicator clusters	Very little adaptive capacity or resilience/ "bounce-back" capacity	Some adaptive capacity and resilience/"bounce-back" capacity	Adequate capacity for adaptation and resilience/"bounce-back" capacity, but not yet acted on	Climate resilience and capacity to bounce forward	Transformative adaptation
The proportion of the population served with risk-reducing infrastructure (paved roads, storm and surface drainage, piped water…) and services relevant to resilience (including health care, emergency services, policing/rule of law) and the institutions needed for such provision	0–30% of the urban center's population served; most of those unserved or inadequately served living in informal settlements.	30–80% of the urban center's population served; most of those unserved or inadequately served living in informal settlements.	80–100% of the urban center's population served; most of those unserved or inadequately served living in informal settlements.	Most/all of the urban center's population with these and with an active adaptation policy identifying current and probable future risks and with an institutional structure to encourage and support action by all sectors and agencies. In many cities, also upgrade aging infrastructure.	Urban centers that have integrated their development and adaptation policies and investments within an understanding of the need for mitigation and sustainable ecological footprints.
The proportion of the population living in legal housing built with permanent materials (meeting health and safety standards)				Active program to improve conditions, infrastructure, and services to informal settlements and low-income areas. Identify and act on areas with higher/ increasing risks. Revise building standards.	Land use planning and management successfully providing safe land for housing, avoiding areas at risk and taking account of mitigation.
Proportion of urban centers covered	Most urban centers in low-income and many in middle-income nations.	Many urban centers in many low-income nations; most urban centers in most middle-income nations.	Virtually all urban centers in high-income nations, many in middle-income nations.	A small proportion of cities in high-income and upper-middle-income nations.	Some innovative city governments thinking of this and taking some initial steps.
Estimated number of people living in such urban centers	1 billion	1.5 billion	1 billion	Very small	
Infrastructure deficit	Much of the built up area lacking infrastructure				Most or all the built up area with infrastructure (paved roads, covered drains, piped water…)
Local government investment capacity	Very little or no local investment capacity				Substantial local investment capacity
Occurrence of disasters from extreme weather[a]	Very common				Uncommon (mostly due to risk-reducing infrastructure, services, and good quality buildings available to almost all the population)
Examples	Dar es Salaam, Dhaka	Nairobi, Mumbai	Most cities in high-income nations	Cities such as New York; London, Durban, and Manizales with some progress	
Implications for climate change adaptation	Very limited capacity to adapt. Very large deficits in infrastructure and in institutional capacity. Very large numbers exposed to risk if these are also in locations with high levels of risk from climate change.	Some capacity to adapt, especially if this can be combined with development, but difficult to get city governments to act. Particular problems for those urban centers in locations with high levels of risk from climate change.	Strong basis for adaptation, but needs to be acted on and to influence city government and many of its sectoral agencies.	City government that is managing land use changes as well as having adaptation integrated into all sectors.	City government with capacity to influence and work with neighboring local government units. Also with land use changes managed to protect eco-system services and support mitigation.

Notes: For cities that are made up of different local government areas, it would be possible to apply the above at an intra-city or intra-metropolitan scale. For instance, for many large Latin American, Asian and African cities, there are local government areas that would fit in each of the first three categories.

[a]See text in regard to disasters and extensive risk (United Nations, 2011).

The increasing concentration of the world's population in urban centers means greater opportunities for adaptation but more concentrated risk if they are not acted on. Many urban governments lack the capacity to do so, especially those in low- and lower-middle-income nations. The result is large deficiencies in infrastructure and services. Urban centers in high-income nations, although much better served, may also face particular challenges—for instance, aging infrastructure and the need to adapt energy systems, building stock, infrastructure, and services to the altered risk set that climate change will bring (see Zimmerman and Faris (2010) and Solecki (2012) for discussions of this for New York). Many studies have shown that working with a range of government and civil society institutions at local and supra-local levels increases the effectiveness of urban adaptation efforts; support and enabling frameworks from higher levels of government were also found to be helpful (see Section 8.4 and many of the studies listed in Box 8-1).

8.1.4. Vulnerability and Resilience

For each of the direct and indirect impacts of climate change, there are groups of urban dwellers that face higher risks (illness, injury, mortality, damage to or loss of homes and assets, disruption to incomes) (Hardoy and Pandiella, 2009; Mitlin and Satterthwaite, 2013). Age may be a factor (for instance infants and elderly people are more sensitive to particular hazards such as heat stress) or health status (those with particular diseases, injuries, or disabilities may be more sensitive to these impacts). Or it may be that they live in buildings or in locations facing greater risks—for instance on coasts or by rivers with increased flood risks—or that they lack coping capacities. Women may face higher risks in their work and constraints on adaptation if they face discrimination in access to labor markets, resources, finance, services, and influence (see Box CC-GC). These are often termed vulnerable groups—although, to state the obvious, they are vulnerable to direct climate change impacts only to the extent that the hazard actually poses a risk. Remove people's exposure to the hazard (e.g., provide drains that prevent flooding) and there is limited or no impact. Infants may face serious health risks when water supplies are contaminated by flooding, but rapid and effective treatment for diarrhea and quickly re-establishing availability of drinking quality water greatly reduces impacts (Bartlett, 2008). Adaptations by individuals, households, communities, private enterprises, or government service providers can all reduce risks.

Adaptation in a particular area or settlement may have clear benefits for the inhabitants there, but can also have knock-on effects on the well-being of inhabitants in other areas. Diverting a river course or building an embankment to protect new development may prevent flooding in one location, but may cause or increase flooding somewhere else (see Revi, 2005, for Mumbai; Alam and Rabbani, 2007, for Dhaka).

Assessments of vulnerability to climate change draws on assessments in other contexts—including the vulnerability of low-income groups to stresses and shocks (e.g., Chambers, 1989; Pryer, 2003) and to disasters (Cannon, 1994; Manyena, 2006). The term is generally used in relation to an inability to cope with external changes including avoiding harm when exposed to a hazard. This includes people's inability to avoid the hazard (exposure), anticipate it, and take measures to avoid it or limit its impact; cope with it; and recover from it (Hardoy and Pandiella, 2009). Vulnerable groups may be identified on the basis of any of these four factors. The definition of resilience used in the WGII AR5 when applied to urban centers means the ability of urban centers (and their populations, enterprises, and governments) and the systems on which they depend to anticipate, reduce, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner (see the Glossary).

The term vulnerability is also applied to sectors, including food processing, tourism, water, energy, and mobility infrastructure and their cross-linkages, for instance, the dependency of perishable commodities on efficient transport. Much tourism is sensitive to climate change, which can damage key tourist assets such as coral reefs and beaches or make particular locations less attractive to tourists because of more extreme weather. The term is also applied to natural systems/ecosystems (e.g., mangroves, coastal wetlands, urban tree canopy). If the adaptive capacity of these systems is increased, they can also provide natural protection from the impacts of climate change in urban areas (see, e.g., Sections 8.2.4.5, 8.3.3.7 for more details).

8.1.4.1. Differentials in Risk and Vulnerability within and between Urban Centers

In urban centers where virtually all buildings meet health and safety standards, where land use planning prevents developments on sites at risk, and where there is universal provision for infrastructure and basic services, the exposure differentials between high- and low-income groups to climate-related risk are quite low. Having low income and few assets in such urban centers does not necessarily imply greater vulnerability to climate change (Mitlin and Satterthwaite, 2013). But typically, the larger the deficit in infrastructure and service provision, the larger the differentials in exposure to most climate change impacts between income groups. Low-income groups in low- and middle-income nations are often disproportionately vulnerable because of poor quality and insecure housing; inadequate infrastructure; and lack of provision for health care, emergency services, and disaster risk reduction (UNISDR, 2009; IFRC, 2010; UN-HABITAT, 2011a; IPCC, 2012; Mitlin and Satterthwaite, 2013). Most deaths from disasters are concentrated in low- and middle-income countries—including more than 95% of deaths from natural disasters between 1970 and 2008 (IPCC, 2012). More than 95% of the deaths from storms and floods registered on the EM-DAT from 2000 to September 2013 were in low- and middle-income nations.[1]

An analysis of annual fatalities from tropical cyclones showed these to be heavily concentrated in low-income nations even though there was high exposure in many upper-middle- and high-income nations (and these nations had larger economic losses; UNISDR, 2009). These analyses do not separate rural and urban populations—but there is a growing body of evidence that most urban deaths from extreme weather events are in low-income and lower-middle-income countries (UNISDR, 2009; IFRC, 2010). Analyses of risks across many cities usually show the cities at highest risk from extreme weather or particular kinds of such weather

[1] These are drawn from data in the The International Disaster Database EM-DAT accessed on September 16, 2013.

(e.g., floods) to be primarily in high-income countries (Munich Re, 2004; Hallegatte et al., 2013). But this is because these analyses are based on estimates of economic costs or economic losses. If they were based instead on deaths and injuries, the ranking would change fundamentally (see also Balica et al., 2012). The official statistics on disaster deaths are also known to considerably understate total deaths, in part because many deaths go unrecorded, in part because of the criteria that a disaster event has to meet to be included (one of the following criteria must be fulfilled: ten or more people reported killed; 100 or more people reported affected; declaration of a state of emergency; or call for international assistance) (UNISDR, 2009).

There are dramatic examples of extreme weather events in high-income countries with very large impacts, including high mortality. But the analyses in UNISDR (2009) and IFRC (2010), and the reports of deaths from extreme weather in many of the case studies listed in Box 8-1, suggest that most extreme weather disaster deaths in urban centers are in low- and lower-middle-income nations, and that risks are concentrated in informal settlements. As noted by IPCC (2012), the occupants of these settlements are typically more exposed to climate events with limited or no hazard-reducing infrastructure, low-quality housing, and limited capacity to cope.

Where provision for adequate housing, infrastructure, and services is most lacking, the capacity of individuals, households, and community organizations to anticipate, cope, and recover from the direct and indirect losses and impact of disasters (of which climate-related events are a subset) becomes increasingly important (see Section 8.4). The effectiveness of early warning systems, the speed of response, and the effectiveness of post-disaster response is especially important to those who are more sensitive and have less coping capacity. The effectiveness of such responses depends on an understanding of the specific vulnerabilities, needs, and priorities of different income groups, age groups, and groups that face discrimination, including that faced by women and by particular social or ethnic groups (UN-HABITAT, 2011a).

8.1.4.2. Understanding Resilience for Urban Centers in Relation to Climate Change

In relation to disasters, resilience is usually considered to be the opposite of vulnerability, but vulnerability is often discussed in relation to particular population groups while resilience is more often discussed in relation to the systemic capacity to protect them and reduce the impact of particular hazards through infrastructure or climate-risk sensitive land use management. In recent years, a literature has emerged discussing resilience to climate change for urban centers and what contributes to it (Muller, 2007; Leichenko, 2011; Moench et al., 2011; Pelling, 2011a; Brown et al., 2012; da Silva et al., 2012). Addressing resilience for cities is more than identifying and acting on specific climate change impacts. It looks at the performance of each city's complex and interconnected infrastructure and institutional systems including interdependence between multiple sectors, levels, and risks in a dynamic physical, economic, institutional, and socio-political environment (Kirshen et al., 2008; Gasper et al., 2011). When resilience is considered for cities, certain systemic characteristics are highlighted—for instance flexibility, redundancy, responsiveness, capacity to learn, and safe failure (Tyler et al., 2010; Moench et al., 2011; Brown et al., 2012; da Silva et al., 2012), as well as take account of the multiple interdependencies between different sectors (see Section 8.2).

When a specific city is being considered, the level and forms of resilience are often related to specific local factors, services, and institutions—for instance, for each district in a city, will the storm and surface drains cope with the next heavy rainfall? During hot days, will measures to help those at risk from heat stress reach all high-risk groups (see Box CC-HS for more detail)? Here, resilience is not only the ability to recover from the impact but also the ability to avoid or minimize the need to recover and the capacity to withstand unexpected or unpredicted changes (UNISDR, 2011). An important aspect of resilience is the functioning of institutions to make this possible and the necessary knowledge base (da Silva et al., 2012).The emerging literature on the resilience of cities to climate change also highlights the need to focus on resource availabilities and sinks beyond the urban boundaries. It may also require coordinated actions by institutions in other jurisdictions or higher levels of government, for example, watershed management upstream of a city to reduce flood risks (Ramachandraiah, 2011; Brown et al., 2012). There are also the slow onset impacts that pose particular challenges and that may also be outside the jurisdiction of urban governments—for instance, the impact of drought on agriculture, which can raise food prices and reduce rural incomes and demand for urban services.

Resilience to extreme weather for urban dwellers is strongly influenced by factors already mentioned—the quality of buildings, the effectiveness of land use planning, and the quality and coverage of key infrastructure and services. It is also influenced by the effectiveness of early warning systems and public response measures (IFRC, 2010; UN-HABITAT, 2011a) and by the proportion of households with savings and insurance and able to afford safe, healthy homes. Safety nets for those with insufficient incomes are also important, along with the administrative capacity to ensure these reach those in need. Urban governments have importance for most of this, although their capacity to provide usually depends on the revenue raising powers and legislative and financial support from higher levels of government. These in turn are driven in part by political pressure from urban dwellers and innovation by city governments. Private companies or non-profit institutions may provide some of these but the framework for provision and quality control is provided by local government or local offices or national or provincial government.

Cities in high-income nations and many in middle-income nations have become more resilient to extreme weather (and other possible catalysts for disasters) through a range of measures responding to risks and to the political processes that demand such responses (IFRC, 2010; UN-HABITAT, 2011a; Satterthwaite, 2013). The universal provision of piped water, sewers, drains, health care and emergency services, and standards set and enforced on housing quality and infrastructure were not a response to climate change but what was built over the last 100 to 150 years in response to the needs and demands of residents. This has produced what can be termed accumulated resilience in the built environment to extreme weather and built the capacity of local governments to act on risk reduction (e.g., Hardoy and Ruete, 2013, on Rosario, Argentina). In addition, it helped build the institutions, finances, and governance systems that can support climate change adaptation (Satterthwaite, 2013). Building and infrastructure standards can be adjusted as required

(if there is infrastructure in place that can be adjusted, e.g., by increasing capacity for storm and surface water drainage systems). Existing levels of service provision can be modified to take into account new risks or risk levels, as can city planning and land use management (e.g., by keeping city expansion away from areas facing higher risk levels). Private sector investments can support these kinds of adjustments (e.g., changing insurance premiums and coverage) (IFRC, 2010; UN-HABITAT, 2011a; UNISDR, 2013). All of these provide the foundation on which to build adaptive capacity to withstand climate change-related direct and indirect impacts.

Whether this will happen depends on willingness of urban governments to take this on, the demands of local inhabitants and their capacity to organize and press for change, and the capacity for learning and cooperation within local institutions. Obviously, it also depends on global agreements that slow and stop the increases in risk from GHG emissions and other drivers of climate change. Many cities with accumulated resilience may still not be equipped to respond to the changed hazards and risks associated with climate change (IPCC, 2012). The issue here becomes whether the institutions and political pressures that built the accumulated resilience are able to shift to resilience building as a directed process—and to respond dynamically and effectively to evolving and changing climate-related risks (and the evolving and changing knowledge bases that supports this).

For urban centers with little accumulated resilience, resilience as a process is also important, both to help reduce over time the (often very large) deficiencies in most or all the infrastructure, services, and regulatory frameworks that provide resilience in high-income nations and to build resilience to climate change impacts (see Table 8-2). For around a third of the world's urban population, this has to be done in a context of limited incomes and assets and poor living conditions and little current coping capacity to stresses or shocks (UNISDR, 2009; IPCC, 2012). Just an increase in the price of food staples, a drop in income, or a new cost, such as medicine for a sick family member, can quickly mean inadequate food, hunger, and reduced capacity to work (Mitlin and Satterthwaite, 2013).

This implies the need for a specific perspective on how climate change adaptation must be supported. It highlights the intimate relationship between resilience to climate change impacts and the quality of governance, especially local governance. The government's capacity and willingness to listen to, work with, support, and serve those who lack resilience is fundamental (IPCC, 2012). This is demonstrated by the many successful partnerships between local government and grassroots organizations formed by residents of informal settlements that have built or improved homes and neighborhoods (see Section 8.4).

Thus, resilience can be considered in relation to individuals/households, communities, and urban centers. In each of these, it includes the capacity to undertake anticipatory adaptation—action that avoids or reduces a climate change impact, for instance, by living in a safe location, having a safe house, or having risk-reducing infrastructure. It also includes reactive adaptation to cope with the impact of an event, to "bounce back" to the previous state (Shaw and Theobald, 2011). For urban centers, "bouncing back" includes the government capacity to rapidly restore key services and repair infrastructure. Ideally, for climate change adaptation, responses by urban populations, enterprises, and governments should allow "bounce forward" to a more resilient state. This is discussed in disaster risk reduction and is termed "building-back better" (Lyons, 2009). This is part of the shift from resilience to transformative adaptation shown in Table 8-2 where urban centers have integrated their development, disaster risk reduction, and adaptation policies and investments within an understanding of the need for mitigation and sustainable ecological footprints (see also Pelling and Dill, 2010; Manyena et al., 2011; Shaw and Theobald, 2011).

8.1.5. Conclusions from the Fourth Assessment Report (AR4) and New Issues Raised by this Chapter

AR4's chapter on Industries, Settlements, and Human Society (Wilbanks et al., 2007) notes that variability in environmental conditions has always been a given, but that when change is more extreme, persistent, or rapid than has been experienced in the past, especially if it is not foreseen and capacities for adaptation are limited, the risks will increase (WGII AR4 Section 7.1.1). The chapter also noted that, except for abrupt extreme events, climate change impacts are not currently dominant issues for urban centers (WGII AR4 Section 7.1.3). Their importance lies in their interaction with other stressors, which may include rapid population growth, political instability, poverty and inequality, ineffective local governments, jurisdictional fragmentation, and aging or inadequate infrastructure (WGII AR4 Section 7.2). Key challenges identified for turning attention to adaptation include the difficulties of estimating and projecting the magnitudes of climate risk in particular places and sectors with precision and a weak knowledge base on the costs of adaptation (issues that are still challenges today).

Wilbanks et al. (2007) describe how the interactions between urbanization and climate change have led to concentrations of urban populations in low-income nations with weak adaptive capacity. They also describe the interactions between climate change and a globalized economy with long supply chains, resulting in impacts spreading from directly affected areas and sectors to other areas and sectors through complex linkages (WGII AR4 Section 7.2). Many impacts will be unanticipated and overall effects are poorly estimated when only direct impacts are considered. Key global vulnerabilities include interregional trade and migration patterns. This chapter also describes how climate change impacts and most vulnerabilities are influenced by local contexts, including geographic location, the climate sensitivity of enterprises located there, development pathways, and population groups unable to avoid dangerous sites and homes (WGII AR4 Sections 7.3, 7.4.3). Key risks are most often related to climate phenomena that exceed thresholds for adaptation (e.g., extreme weather or abrupt changes) and limited resources or institutional capacities to reduce risk and cope (e.g., with increased demands on water and energy supplies and often on health care and emergency response systems).

Individual adaptation may not produce systemic adaptation. In addition, adaptation of systems may not benefit all individuals or households, because of the different vulnerability of particular groups and places (WGII AR4 Section 7.6.6). Adaptation will be well served by a greater awareness of threats and alternatives beyond historical experience and current access to finance. Technological innovation for climate adaptation comes largely from industry and services that are motivated by market

signals, which may not be well matched with adaptation needs and residual uncertainties. Many are incremental adjustments to current business activities.

For the types of infrastructure most at risk—including most transport, drainage, and electricity transmission systems and many water supply abstraction and treatment works—reserve margins can be increased and back-up capacity developed (WGII AR4 Section 7.6.4). Adaptation of infrastructure and building stock often depends on changes in the institutions and governance framework, for example, in planning regulations and building codes. Climate change has become one of many changes to be understood and planned for by local managers and decision makers (WGII AR4 Section 7.6.7). For instance, planning guidance and risk management by insurers will have roles in locational choice for industry.

Since AR4, a much larger and more diverse literature has accrued on current and potential climate change risks for urban populations and centers (see Section 8.2). The literature on urban "adaptation" and on building resilience at city and regional scales has also expanded (see Sections 8.3, 8.4) including work on urban centers in low- and middle-income nations (see Box 8-1). Far more city governments have published documents on adaptation. There is more engagement with urban adaptation by some professions, including architects, engineers, urban planners, and disaster risk reduction specialists (Engineers Canada, 2008; UNISDR, 2009; Engineering the Future, 2011; UN-HABITAT, 2011a; da Silva, 2012). There are also assessments and books that focus specifically in climate change and cities with a strong focus on adaptation (Bicknell et al., 2009; Rosenzweig et al., 2011; UN-HABITAT, 2011a; Cartwright et al., 2012; Willems et al., 2012; Bulkeley, 2013).

This makes a concise and comprehensive summary more difficult. But it has also allowed for more clarity on what contributes to resilience in urban centers and systems. Specifically, there is now:

- A more detailed understanding of key urban climate processes, including drivers of climate change, and improved analytical and down-scaled integrated assessment models at regional and city scale
- A more detailed understanding on the governance of adaptation in urban centers and the adaptation responses being considered or taken; this includes a large and important gray literature produced by or for city governments and some international agencies and, in many high-income and some middle-income nations, support for this from higher levels of government
- More nuanced understanding of the many ways in which poverty and discrimination exacerbates vulnerability to climate impacts (see also Chapter 13)
- More detailed studies on particular built environment responses to promote adaptation (see, e.g., the growth in the literature on green and white roofs)
- More case studies of community-based adaptation and its potential contributions and limitations
- More consideration of the role of ecosystem services and of green (land) and blue (water) infrastructure in adaptation
- More consideration of the financing, enabling, and supporting of adaptation for households and enterprises
- More on learning from innovation in disaster risk reduction
- A greater appreciation of the interdependencies between different infrastructure networks and of the importance of "hard" infrastructure and of the institutions that plan and manage it
- More examples of city governments and their networks contributing to national and global discussions of climate change adaptation (and mitigation), including establishing voluntary commitments (see, e.g., the Durban Adaptation Charter for local governments) and engaging with the Conference of Parties.

A range of key uncertainties and research priorities emerge from the literature reviewed in this chapter:

- The limits to understanding and predicting impacts of climate change at a fine-grained geographic and sectoral scale
- Inadequate knowledge on the vulnerabilities of urban citizens and enterprises to the direct impacts of climate change, to second- and third-order impacts, and to the interdependence between systems
- Inadequate knowledge on the vulnerability of the built environment, buildings, building components, building materials, and the construction industry to the direct and indirect impacts of climate change and of the most effective responses for new-build and for retrofitting
- Inadequate knowledge on the adaptation potentials for each urban center (and its government) and their costs, and on the limits on what adaptation can achieve (informed by a new literature on loss and damage)
- Serious limitations on geophysical, biological, and socioeconomic data needed for adaptation at all geographic scales, including data on nature-society links and local (fine-scale) contexts (see WMO, 2008) and hazards
- Uncertainties about trends in societal, economic, and technological change with or without climate change, including the social and political underpinnings of effective adaptation
- Understanding the different impacts and adaptation responses for rapid and slow-onset disasters
- Developing the metrics for measuring and monitoring success in adaptation in each urban center:
  - Human deaths and injuries from extreme weather
  - Number of permanently or temporarily displaced people and others directly and indirectly affected
  - Impacts on properties, measured in terms of numbers of buildings damaged or destroyed
  - Impacts on infrastructure, services, and lifelines
  - Impacts on ecosystem services
  - Impacts on crops and agricultural systems and on disease vectors
  - Impacts on psychological well-being and sense of security
  - Financial or economic loss (including insurance loss)
  - Impacts on individual, household, and community coping capacities and need for external assistance.

8.2. Urbanization Processes, Climate Change Risks, and Impacts

8.2.1. Introduction

This section assesses the connections between urbanization and climate change in relation to patterns and conditions of climate risk, impact,

and vulnerability. The focus is on urbanization's local, regional, and global environmental consequences and the processes that may lead to increased risk exposure, constrain people in high-risk livelihoods and residences, and generate vulnerabilities in critical infrastructure and services. Understanding urbanization and associated risk and vulnerability distributions is critical for an effective response to climate change threats and their impacts (Vale and Campanella, 2005; Bicknell et al., 2009; Solnit, 2009; Bulkeley, 2010; Romero-Lankao and Qin, 2011). It is also critical for the promotion of sustainable urban habitats and the transition to increased urban resilience. There is a particular interest here in the ability of cities to respond to environmental crises, and the resilience and sustainability of cities (Solecki et al., 2011; Solecki, 2012).

The section assesses the direct impacts of climate change on urban populations and urban systems. Together, with shifts in urbanization, these direct impacts change the profile of societal risk and vulnerability. Both can alter transition pathways that lead toward greater resilience and sustainable practices and the basis of how such practices are managed within a community. Understanding and acting on the connections between climate change and urbanization are also crucial because changes in one can affect the other. We investigate a range of direct impacts including those on physical and ecological systems, social and economic systems, and coupled human-natural systems. Where relevant to understanding, cascading impacts (where systems are tightly coupled) and secondary (indirect) impacts also are noted.

8.2.2. Urbanization: Conditions, Processes, and Systems within Cities

8.2.2.1. Magnitude and Connections to Climate Change

The spatial, temporal, and sustainability-related qualities of urbanization are important for understanding the shifting, complex interactions between climate change and urban growth. Given the significant and usually rising levels of urbanization (Section 8.1.3), a growing proportion of the world's population will be exposed to the direct impacts of climate change in urban areas (de Sherbinin et al., 2007; Revi, 2008; UN-HABITAT, 2011a). Urban centers in Africa, Asia, and Latin America with fewer than a million inhabitants are where most population growth is expected (UN DESA Population Division, 2012), but these smaller centers are "often institutionally weak and unable to promote effective mitigation and adaptation actions" (Romero-Lankao and Dodman, 2011, p. 114).

Urbanization alters local environments via a series of physical phenomena that can result in local environmental stresses. These include urban heat islands (higher temperatures, particularly at night, in comparison to outlying rural locations) and local flooding that can be exacerbated by climate change. It is critical to understand the interplay among the urbanization process, current local environmental change, and accelerating climate change. For example, in the past, long-term trends in surface air temperature in urban centers have been found to be associated with the intensity of urbanization (Kalnay et al., 2006; He et al., 2007; Ren et al., 2007; Stone, 2007; Fujibe, 2008, 2011; Jung, 2008; Rim, 2009; Sajjad et al., 2009; Santos and Leite, 2009; Tayanç et al., 2009; Kolokotroni et al., 2010; Chen et al., 2011; Iqbal and Quamar, 2011). Climate change can influence these microclimate and localized regional climate dynamics. For example, urbanization (micro scale to meso scale) can strengthen and/or increase the range of the local urban heat island (UHI) altering small-scale processes, such as a land-sea breeze effect, katabatic winds, etc., and modifying synoptic scale meteorology (e.g., changes in the position of high pressure systems in relation to UHI events). Climate modeling exercises indicate an "urban effect" that leads locally to higher temperatures. Building material properties are influential in creating different urban climate temperature regimes, which can alter energy demand for climate control systems in buildings (Jackson et al., 2010).

The dense nature of many large cities has a pronounced influence on anthropogenic heat emissions and surface roughness, linked to the level of wealth, energy consumption, and micro and regional climate conditions. Anthropogenic heat fluxes across large cities can average within a range of approximately 10 to 150 W m^{-2} but over small areas of the city can be three to four times these values or even more (Flanner, 2009; Allen et al., 2011). In London, an annual mean anthropogenic heat flux of 10.9 has been observed (Iamarino et al., 2012) with higher values in small areas of the city exceeding 100 (Allen et al., 2011) with a similar range found in Singapore (13 W m^{-2} in low-density residential areas and 113 W m^{-2} in high density commercial areas (Quah and Roth, 2012). Values locally greater than 1000 W m^{-2} have been calculated in Tokyo (Ichinose et al., 1999). Strong seasonal, diurnal, and meteorological variability in temperature also influence the level of significance of urbanization-related changes on specific cities.

The large spatial extent and significant amount of built environment of megacities (10 million or more inhabitants) can have significant impacts on the local and regional energy balance and associated weather, climate, and related environmental qualities such as air quality. Grimmond (2011) found increasing evidence that cities can influence weather (e.g., rainfall, lightning) through complex urban land use-weather-climate directional feedbacks (see also Ohashi and Kida, 2002). Spatially massive urban centers also can affect downwind locations by raising temperature and negatively impacting air quality (Bohnenstengel et al., 2011). Megacity impact on air flows has been modeled for New York and Tokyo (Holt and Pullen, 2007; Thompson et al., 2007; Holt et al., 2009). Megacity-coastal interactions may impact the hydrological cycle and pollutant removal processes through the development of fog, clouds, and precipitation in cities and adjoining coastal areas (Ohashi and Kida, 2002; Shepherd et al., 2002). Other modeling efforts define building density and design and the scale of urban development as important local determinants of the influence of urbanization on local temperature shifts (Trusilova et al., 2008; Oleson, 2012).

8.2.2.2. Spatiality and Temporal Dimensions

Spatial settlement patterns are a critical factor in the interactions among urbanization, climate-related risks, and vulnerability. One aspect is density, ranging from concentrated to dispersed, with most planned urban settlements decreasing in population density with distance from the core (Solecki and Leichenko, 2006; Seto et al., 2012). In cities with large fringe and unplanned settlements, this pattern can be reversed. In both cases, urban growth is experienced through horizontal expansion and sprawl (UN DESA Population Division, 2012), fostering extensive

networks of critical infrastructure, which are frequently vulnerable to climate change (Rosenzweig et al., 2011; Solecki et al., 2011). Rapid urban population growth in the last decade also has been increasingly marked by growth in vertical density (high-rise living, and working), especially in Asia. Higher density living offers opportunities for resource conservation but also challenges for planning and urban management (Section 8.3.3).

Urbanization is associated with changing dimensions of migration and materials flows into and out of cities and also within them (Grimm et al., 2008). The level of increase (or in some cases decrease) of these conditions creates a dynamic quality of risk in cities. Rapidly changing cities must try to manage this growth through housing and infrastructure development while simultaneously understanding the relative impact of climate change. For example, in sub-Saharan Africa, the combination of relatively high population growth rates and increasing levels of urbanization brings a rise in exposure to climate change impacts (Parnell and Walawege, 2011). The conflation of local environmental change resulting from urbanization with climate change shifts makes the identification and implementation of effective adaptation strategies more difficult. Water shortages, for instance, already a chronic concern for many cities in low- and middle-income nations, typically worsen as the population and demand continue to grow (Muller, 2007). Climate change-related reductions or uncertainties in supply combine with this existing instability to create the conditions for greater management and governance crises (Milly et al., 2008; Gober, 2010).

8.2.2.3. Urbanization and Ecological Sustainability

The urbanization-climate change connection has important implications for ecological sustainability. Climate change can accelerate ecological pressures in cities, as well as interact with existing urban environmental, economic, and political stresses (Wilbanks and Kates, 2010; Leichenko, 2011). This is an especially important in a world where transgressions of key planetary boundaries such as climate change and biodiversity may take humanity out of the globe's "safe operating" space (Rockström et al., 2009, p. 1) into an unsafe and unpredictable future. A study by Trusilova et al. (2008) analyzes the urbanization-induced disturbances of the carbon cycle in Europe through land use change, local climate modification, and atmospheric pollution. This study shows that urban effects spread far beyond the city's boundaries and trigger complex feedback/responses in the biosphere (Trusilova et al., 2008). Urbanization changes land use cover, generally reduces the amount of ecologically intact land, and causes fragmentation of the remaining land, which reduces habitat value for species and increases the likelihood of further ecological degradation.

The linkage between urbanization, ecological sustainability, and climate change is well illustrated by the example of New Orleans. This city's geophysical vulnerability is shaped by its low-lying location, accelerating subsidence, rising sea levels, and heightened intensity and frequency of hurricanes—a combination of natural phenomena exacerbated by settlement decisions, canal development, loss of barrier wetlands, extraction of oil and natural gas, and the design, construction, and failure of protective structures and rainfall storage" (Wilbanks and Kates, 2010, p. 726; see also Ernstson et al., 2010). For cities in arid regions, already struggling with water shortages often in the context of rising demand, climate change may further reduce water availability because of shifts in precipitation and/or evaporation (Gober, 2010).

8.2.2.4. Regional Differences and Context-Specific Risks

Case studies and regional reviews assessing urban vulnerabilities to climate change have revealed diverse physical and societal challenges and large differences in levels of adaptive capacity (Hunt and Watkiss, 2011; Rosenzweig et al., 2011). Research on African cities (Simon, 2010; Kithiia, 2011; Castán Broto et al., 2013) has highlighted the lack of capacity and awareness of climate change, and often extremely high levels of vulnerability among the continent's large and rapidly growing urban poor populations. Other reviews have considered cities in Latin America (Hardoy and Romero-Lankao, 2011; Luque et al., 2013), North America (Zimmerman and Faris, 2011), Europe (Carter, 2011), and Asia (Alam and Rabbani, 2007; Kovats and Akhtar, 2008; Revi, 2008; Birkmann et al., 2010; Liu and Deng, 2011). The global distribution of urban risks is highly context specific, dynamic, and uneven among and within regions. Absolute exposure to extreme events over the next few decades will be concentrated in large cities and countries with urban populations in low-lying coastal areas, as in many Asian nations (McGranahan et al., 2007). Settlements located in river flood plains also are prone to flooding during extreme or persistent precipitation/severe storm conditions.

Many cities include dangerous sites, such as steep slopes, low lands adjacent to unprotected riverbanks, and ocean shorelines, and have structures that do not meet building codes (Hardoy et al., 2001; Pelling, 2003). Context-specific risks and associated vulnerability also relates to the socioeconomic status of residents. Women, children, health-compromised people, and the elderly in informal settlements are generally most vulnerable to climate change impacts. Poor access to infrastructure and transport, low incomes, limited assets, and dangerous locations can combine to put them at high risk from disasters (Moser and Satterthwaite, 2009).

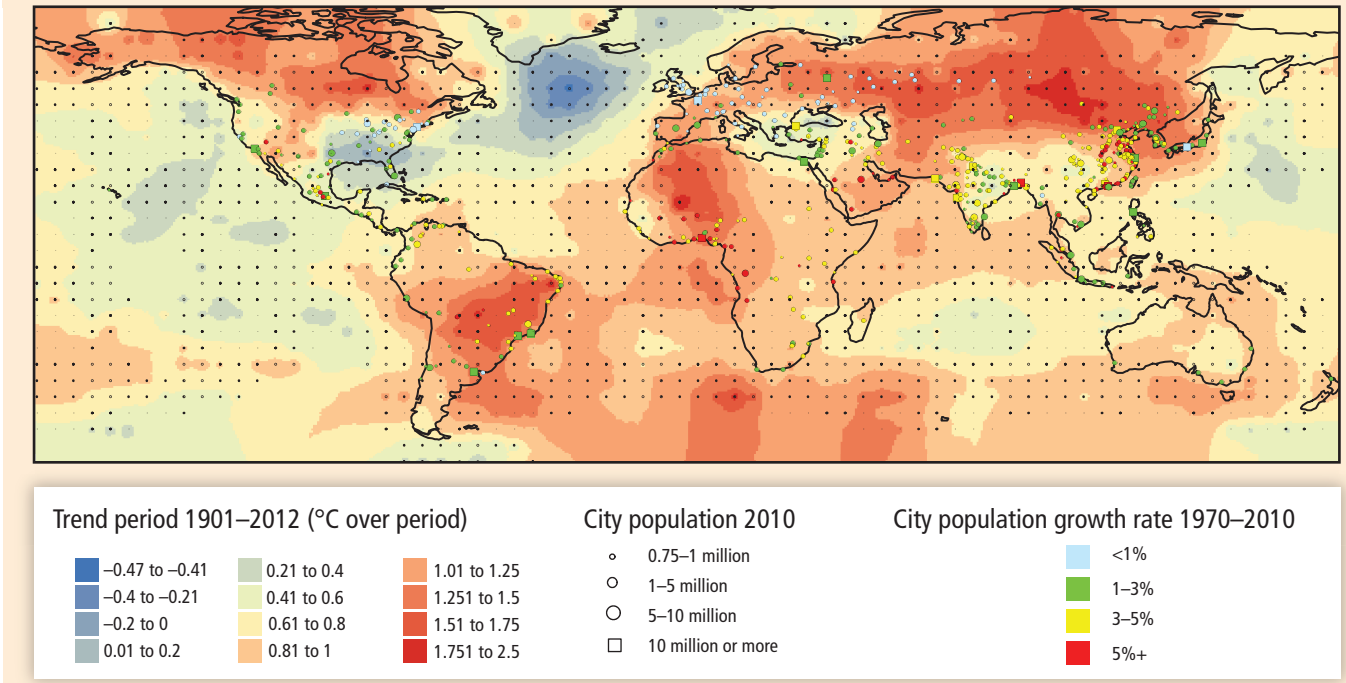
8.2.3. Climate Change and Variability Impacts: Primary (Direct) and Secondary (Indirect) Impacts

Climate change will lead to increased frequency, intensity, and/or duration of extreme weather events such as heavy rainfall, warm spells and heat events, drought, intense storm surges, and associated sea level rise (IPCC, 2007, 2012; Hunt and Watkiss, 2011; Romero-Lankao and Dodman, 2011; Rosenzweig et al., 2011). Several urban aspects of these changes are described below.

8.2.3.1. Urban Temperature Variation: Means and Extremes

The three maps in Figure 8-3 show where the world's largest urban agglomerations are concentrated in relation to changes in observed and projected temperature. Figure 8-3a shows the location of the largest urban agglomerations in 2010 against the backdrop of the observed history of climate-induced temperature rise (1901–2012). The dot for each urban agglomeration is color-coded according to its population

(a) Large urban agglomerations 2010 with observed climate change, trend period 1901–2012



(b) Large urban agglomerations 2025 with projected climate change for the mid-21st century using RCP2.6

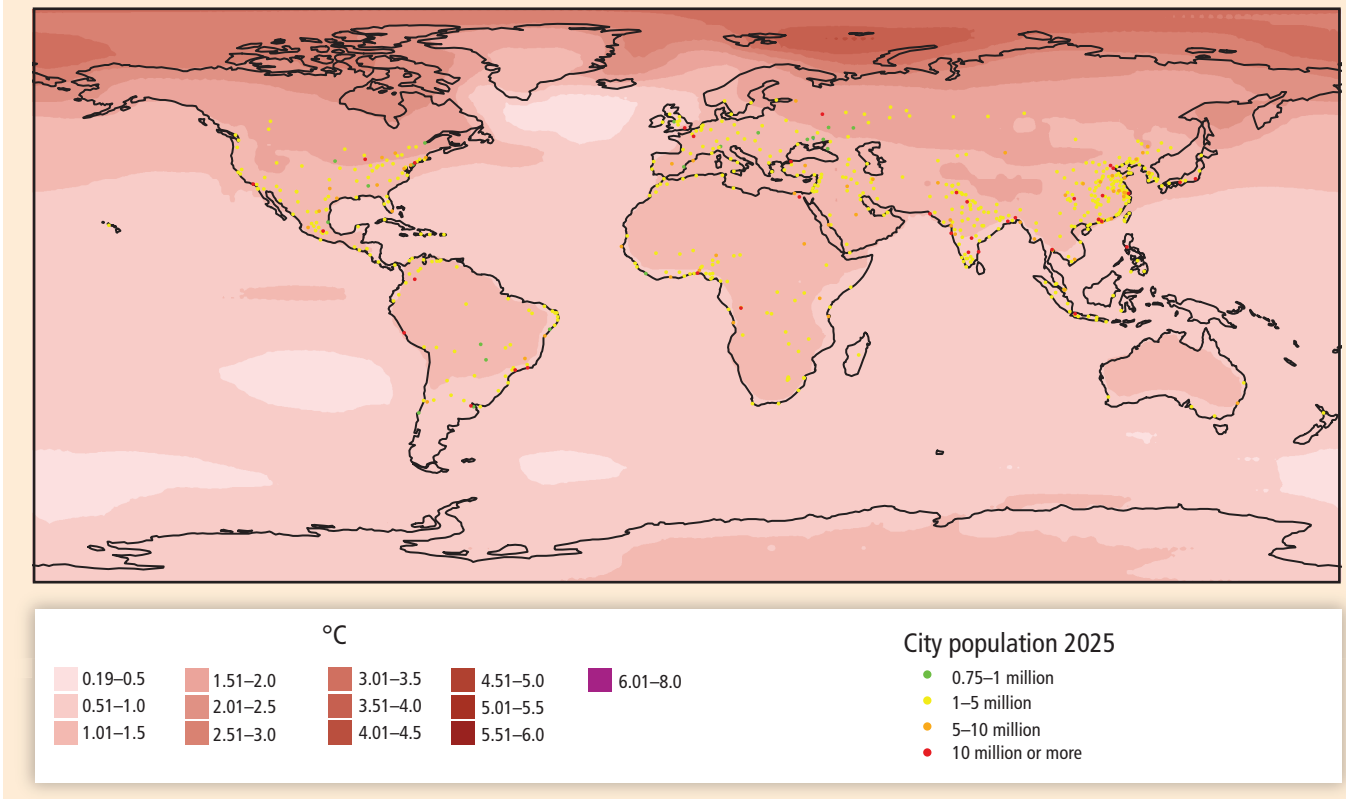
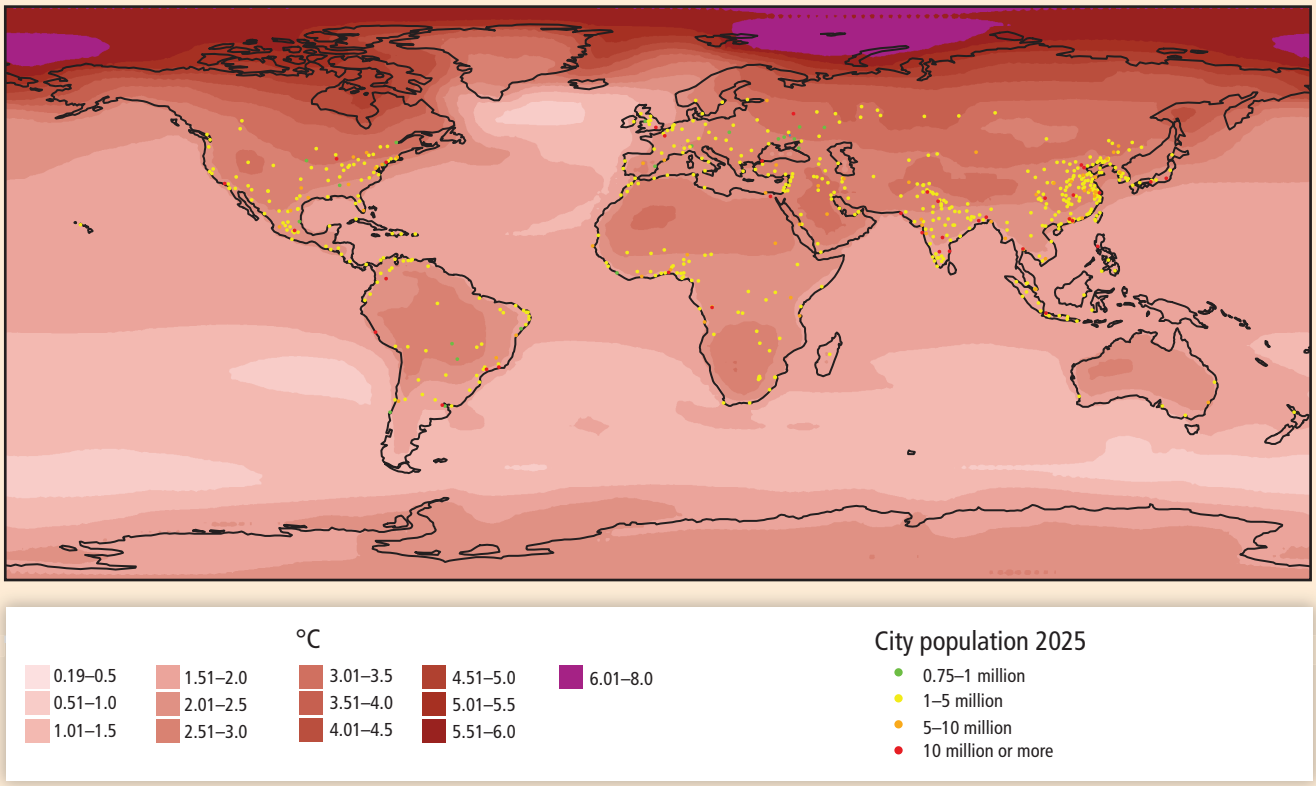


Figure 8-3 | Large urban agglomerations and temperature change (maps drawn from IPCC, 2013; urban agglomeration population and population growth data from UN DESA Population Division, 2012).

Continued next page →

Figure 8-3 (continued)

(c) Large urban agglomerations 2025 with projected climate change for the mid-21st century using RCP8.5



growth rate between 1970 and 2010. Those that had the most rapid population growth rates for these 4 decades are strongly clustered in Asia (especially in China and India) and in Latin America and sub-Saharan Africa (with many on the coast). This map highlights the temperature rise of greater than 1°C in areas in north and central Asia, western Africa, South America, and parts of North America, indicating the potential differential exposure of large cities to climate risk.

Figure 8-3b shows the location of the largest urban agglomerations according to projected populations for 2025 within the world map showing projected temperature changes for the mid-21st century, using Representative Concentration Pathway 2.6 (RCP2.6). This is a scenario with strong mitigation. Projected populations for urban agglomerations were not made up to 2050 because there is no reliable basis for making these. Each urban agglomeration's future population is much influenced by its economic performance and by social, demographic, economic, and political changes that cannot be predicted so far into the future. Assuming that almost all the large urban agglomerations in 2025 will still be large urban agglomerations in 2050, Figure 8-3b suggests that a number of large urban agglomerations in almost all continents, will be exposed to a temperature rise of greater than 1.5°C (over preindustrial levels) by mid-century, using the RCP2.6 scenario (IPCC, 2013).

Figure 8-3c shows a similar map showing projected temperature changes for the mid-21st century but using the RCP8.5 scenario. This scenario, based on unchanged current GHG emission trends by mid-century, shows that the bulk of the world's population living in the largest urban agglomerations (based on their 2025 populations) will be exposed to a minimum 2°C temperature rise over preindustrial levels, excluding urban heat island effects. By late-century, under the RCP2.6 scenario, a number of the urban agglomerations that were among the largest in 2025 will be exposed to temperature rise of up to 2.5°C over preindustrial levels (excluding urban heat island effects), especially in the high latitudes. This implies that mean temperature rise in some cities could be greater than 4°C. The RCP8.5 scenario by late century (with unchanged current GHG emission trends) shows that the bulk of the world's population living in large urban agglomerations will be exposed to a minimum 2.5°C temperature rise. Some cities in high latitudes experience a mean 3.5°C rise, or greater than 5°C when combined with UHI effects. Peak seasonal temperatures could be even higher. Temperature increases of 6°C to 8°C in the Arctic and temperature rise in Antarctica would contribute to sea level rise that would impact coastal cities across the world.

Increased frequency of hot days and warm spells will exacerbate urban heat island effects, causing heat-related health problems (Hajat et al., 2010) and, possibly, increased air pollution (Campbell-Lendrum and Corvalan, 2007; Blake et al., 2011), as well as an increase in energy demand for warm season cooling (Lemonsu et al., 2013). Conversely, widespread reduction in periods of very cold weather will mean a

decline in heating demands (Mideksa and Kallbekken, 2010) and potential reduction in mortality from cold waves.

Climate change will modify UHIs in cities. Recent studies with physically based models (McCarthy et al., 2010; Früh et al., 2011; Oleson, 2012) show mixed signals, with reductions in UHI in many areas of the world and increases in some in response to climate change simulations. London's annual number of nights with heat islands stronger than 4ºC has increased by 4 days per decade since the late 1950s; meanwhile, the average nocturnal heat island intensity rose by approximately 0.1°C per decade over the same period (Wilby, 2007). Projections suggest that by 2050, London's nocturnal UHI in August could rise another 0.5°C, representing a 40% increase in the number of nights with intense UHI episodes (Wilby, 2007). However, McCarthy et al. (2011), looking specifically at London and Manchester, found 0.1ºC or less (T_{min}) increase in expected UHI by the 2050s. Future projections of UHI under global warming conditions were also conducted for Tokyo, where a potential increase of the UHI intensity of 0.5ºC was defined (Adachi et al., 2012). Adachi et al. (2012) model an increase in UHI from 1.0ºC to 1.5ºC by the 2070s. In addition to the greater UHI intensity, air temperature in August is projected to increase about 2ºC by the 2070s according to an average of five Global Climate Models (GCMs) under the *Special Report on Emissions Scenarios* (SRES) A1B scenario (the range of uncertainty in GCMs is about 2ºC).

Climate change in New York City is expected to increase extended heat waves, thus exacerbating existing UHI conditions (Rosenzweig et al., 2009). Increased nighttime minimum temperatures are associated with increased cooling demand and health-related stresses. For cities in India, the implications of future climate for connections between urbanization and the development of UHI have been defined (Mohan et al., 2011a,b, 2012). Overall, the current trend of increasingly frequent extreme events is expected to increase with climate change (Manton, 2010). Comparison of the annual mean minimum temperatures of two stations in Delhi (Safdarjung and Palam) since the 1970s shows night temperature trends synchronizing with the city's pace of expansion (Mohan et al., 2011a).

8.2.3.2. Drought and Water Scarcity: Means and Extremes

Drought can have many effects in urban areas, including increases in water shortages, electricity shortages (where hydropower is a source), water-related diseases (through use of contaminated water), and food prices and food insecurity from reduced supplies. These may all contribute to negative economic impacts and increased rural to urban migration (Vairavamoorthy et al., 2008; Herrfahrdt-Pähle, 2010; Farley et al., 2011). An estimated 150 million people currently live in cities with perennial water shortage, defined as less than 100 liters per person per day of sustainable surface and groundwater flow within their urban extent. Averages across all climate change scenarios, noting the role of demographic growth, suggest a large increase in this number, possibly up to 1 billion by 2050 (McDonald et al., 2011).

8.2.3.3. Coastal Flooding, Sea Level Rise, and Storm Surge

Sea level rise represents one of the primary shifts in urban climate change risks, given the increasing concentration of urban populations in coastal locations and within low-elevation zones (McGranahan et al., 2007). The new IPCC estimates for global mean sea level rise are for between 26 and 98 cm by 2100; this is higher than the 18 to 59 cm projected in AR4 (IPCC, 2013). Rising sea levels, the associated coastal and riverbank erosion, or flooding in conjunction with storm surge could have widespread effects on populations, property, and coastal vegetation and ecosystems, and present threats to commerce, business, and livelihoods (Nicholls, 2004; Dossou and Gléhouenou-Dossou, 2007; Zanchettin et al., 2007; El Banna and Frihy, 2009; Carbognin et al., 2010; Pavri, 2010; Hanson et al., 2011). This is well illustrated by several large-scale recent disasters including Hurricane Sandy in the New York metropolitan region. Lowland areas in coastal cities such as Lagos, Mombasa, or Mumbai are usually more at risk of flooding, especially where there is less provision for drainage (Awuor et al., 2008; Revi, 2008; Adelekan, 2010). Structures on infilled soils in the lowlands of Lagos and Mumbai are more exposed to risks of flood hazards than similar structures built on consolidated materials (Awuor et al., 2008; Revi, 2008; Adelekan, 2010). Many near coastal cities such as Dhaka have sites at risk from both riverine and coastal storm surge (Mehrotra et al., 2011a).

Cities with extensive port facilities and large-scale petro-chemical and energy-related industries are especially vulnerable to risks from increased flooding (Hallegatte et al., 2013). Hanson et al. (2011) estimate the change in flooding by the 2070s in the exposure of large port cities to coastal flooding with scenarios of socioeconomic growth, sea level rise and heightened storm surge, and subsidence. They find that with a 0.5 m rise in sea level, the population at risk could more than triple while asset exposure is expected to increase more than 10-fold. The "top 20" cities identified for both population and asset exposure to coastal flooding in both the current and 2070 rankings are spread across low-, middle-, and high-income nations, but are concentrated in Asian deltaic cities. They include: Mumbai, Guangzhou, Shanghai, Miami, Ho Chi Minh City, Kolkata, New York, Osaka-Kobe, Alexandria, Tokyo, Tianjin, Bangkok, Dhaka, and Hai Phong. Using asset exposure as the metric, cities in high-income nations and in China figure prominently: Miami, New York City, Tokyo, and New Orleans as well as Guangzhou, Shanghai, and Tianjin. Detailed site specific studies can define the local level of sea level rise and other local factors such as harbor development, dredging and erosion, groundwater withdrawal, and subsidence and other factors.

8.2.3.4. Inland Flooding, Hydrological and Geo-Hydrological Hazards at Urban Scale

Exposure to climate related hazards will vary with differences in the geomorphologic characteristics of cities (Luino and Castaldini, 2011). Heavy rainfall and storm surges would impact urban areas through flooding, which in turn can lead to the destruction of properties and public infrastructure, contamination of water sources, water logging, loss of business and livelihood options, and increase in water-borne and water-related diseases, as noted in wide range of studies (de Sherbinin et al., 2007; Dossou and Gléhouenou-Dossou, 2007; Douglas et al., 2008; Kovats and Akhtar, 2008; Revi, 2008; Roberts, 2008; Hardoy and Pandiella, 2009; Nie et al., 2009; Adelekan, 2010; Sharma and Tomar, 2010; Shepherd et al., 2011). Case studies of inland cities have considered the

elevated risk of flooding due to climate change, as in Kampala (Lwasa, 2010) and travel disruptions in Portland (Chang et al., 2010). There have been significant research attempts to improve modelling of the frequency and condition of extreme precipitation events and resulting flooding (Nelson et al., 2008; Olsson et al., 2009; Onof and Arnbjerg-Nielsen, 2009; Sen, 2009; Ranger et al., 2011).

The review on the world-wide impacts of climate change on rainfall extremes and urban drainage by Willems et al. (2012) has shown that typical increases in rainfall intensity at small urban hydrology scales range from 10% to 60% from control periods in the recent past (typically 1961–1990) up to 2100. These changes in extreme short-duration rainfall events may have significant impacts for urban drainage systems and pluvial flooding. Results so far indicate more problems with sewer sub-charging, sewer flooding, and more frequent combined sewer overflow (CSO) spills. Extreme rainfall changes in the range of 10 to 60% may lead to changes in flood and CSO frequencies and volumes in the range 0 to 400% depending on system characteristics. This is because floods and overflows, when runoff or sewer flow thresholds are exceeded, can react to rainfall (changes) in a highly nonlinear way (Willems and Vrac, 2011; Willems et al., 2012; Arnbjerg-Nielsen et al., 2013; Willems, 2013).

8.2.3.5. Emerging Human Health, Disease, and Epidemiology Issues in Cities

WHO and WMO (2012) and Barata et al. (2011) note that climate change may affect the future social and environmental determinants of health, including clean air, safe drinking water, sufficient food, and secure shelter. There is good evidence that temperature extremes (heat and cold) affect health, particularly mortality rates (see Section 11.2.2). Increased warming and physiological stress on human comfort level is predicted in a variety of cities in subtropical, semiarid, and temperate sites (Thorsson et al., 2011; Blazejczyk et al., 2012); see also Figure 8-3. For more discussion on cities and impacts of increased warming in specific regions, see the regional chapters (Chapters 21 to 30).

Recent studies have illustrated the impact of heat stress on urban populations in low- and middle-income countries (see, e.g., Burkart et al., 2011, for Bangladesh and Egondi et al., 2012, for children in Nairobi's informal settlements). Hot days are known to have significant impacts on health that can be exacerbated by both drought conditions and high humidity. Studies in high-income countries show the elderly more vulnerable to heat-related mortality (see Oudin Åström et al., 2011, for a review of this). In urban settings where child mortality is high, extreme temperatures have been shown to have an impact on mortality (e.g., Egondi et al., 2012). People in some occupations are more at risk, as they are exposed to higher temperatures for long durations (see Hoa et al., 2013) and low-income households are more at risk when heat waves disrupt or limit income-earning opportunities (Kovats and Akhtar, 2008, see also Section 11.2.7 for more detailed discussion of occupational heat stress).

Climate change has implications for urban air quality (Athanassiadou et al., 2010), air pollution, and health policy (WGI AR5 Chapter 11). The impacts on urban air quality in particular urban areas are highly uncertain and may include increases and decreases of certain pollutants (Jacob and Winner, 2009; Weaver et al., 2009). Urban air quality in most cities already is compromised by localized air pollution from transport and industry, and often commercial and residential sources. Emerging literature shows strong evidence that climate change will generally increase ozone in the USA and Europe, but that the pattern of that change is not clear, with some areas increasing and some decreasing (Katragkou et al., 2011; Lam et al., 2011). The effects on particulate matter (PM) are also unclear, as are the effects on ozone and PM outside of the USA and Europe (Dawson et al., 2013).

The incidence of asthma exacerbation may be affected by climate change-related increases in ground level ozone exposures (Kinney, 2008; Gamble et al., 2009; O'Neill and Ebi, 2009; Reid et al., 2009; Barata et al., 2011); other pollutants may also be affected, particularly in cities with PM10 and ozone levels far above WHO guidelines (WHO, 2011). Climate change may change the distribution, quantity, and quality of pollen in urban areas, as well as the timing and duration of pollen seasons. WHO and WMO (2012) notes that diarrheal diseases, malnutrition, malaria, and dengue are climate sensitive and, in the absence of appropriate adaptation, could be adversely affected by climate change (see Chapter 11).

8.2.4. Urban Sectors: Exposure and Sensitivity

This section assesses how the observed and forecast direct impacts of climate change influence the exposure of city residents, buildings, infrastructure, and systems to risk. It considers key affected sectors and populations and possible interrelations. Direct impacts include all costs and losses attributed to the impact of hazard events, but exclude systemic impacts, for example, on urban economies through price fluctuations following a disaster or the impact of disaster losses on production chains (UN ECLAC, 1991). Both the temporal and spatial scales of the shifts in climate risk across cities and urbanizing sites in the next few decades are considered. In addition, we analyze the change in the scale and character of risks in cities, as climate extremes, means, and long-term trends (e.g., sea level rise) change.

Climate change will have profound impacts on a broad spectrum of city functions, infrastructure, and services and will interact with and may exacerbate many existing stresses. These impacts can occur both *in situ* and through long-distance connections with other cities and rural sites of resource production and extraction (Wackernagel et al., 2006; Seto et al., 2012). The interaction between climate change and existing environmental stresses can lead to a range of synergies, challenges, and opportunities for adaptation with complex interlinkages and often highly uncertain or nonlinear processes (Ernstson et al., 2010). For example, the 2007 floods in the city of Villahermosa, which covered two-thirds of Tabasco State in Mexico, had serious consequences for the city's economic base, with damages and losses equivalent to 30% of the state's annual GDP (CEPAL, 2008). The flood that struck the Chao Phraya River in 2011 caused a high loss of life and damages to many companies and several industrial estates in Bangkok (estimated local damage and loss was 3.5 trillion yen), but it also disrupted global scale industrial supply chains (Komori et al., 2012). Urban centers serving prosperous agricultural regions are particularly sensitive to climate

change if water supply or particular crops are at risk. In Naivasha, Kenya, drought threatens high-value export-oriented horticulture (Simon, 2010). Urban centers that serve as major tourism destinations may suffer when the weather becomes stormy or excessively hot and leads to a loss of revenue. Recent assessments have projected the rising population and asset exposure in large port cities (Munich Re, 2004; Hanson et al., 2011; see also Section 8.2.3.3), alongside case studies in Copenhagen (Hallegatte et al., 2011b) and Mumbai (Ranger et al., 2011). By 2070, the exposed assets in cities such as Ningbo (China), Dhaka (Bangladesh), and Kolkata (India) may increase by more than 60-fold (Hanson et al., 2011).

Infrastructure will similarly be affected by systemic and cascading climate risks (Hunt and Watkiss, 2011). Climate stresses, particularly extreme events, will have effects across interconnected urban systems, within and across multiple sectors (Gasper et al., 2011). The cascading effects are especially evident in the water, sanitation, energy, transport, and communications sectors, owing to the often tightly coupled character of urban infrastructure systems (see Rosenzweig and Solecki, 2010, for a discussion of this for New York City). The U.S. National Climate Assessment effort has looked at the impacts of climate change on infrastructure, considering the water, land, and energy nexus, as well as on a large number of industries (Skaggs et al., 2012; Wilbanks et al., 2012). These systemic cascades can have both direct and indirect economic impacts (Hallegatte et al., 2011b; Ranger et al., 2011), which can extend from the built environment to urban public health (Frumkin et al., 2008; Keim, 2008). A critical element is the impact for infrastructure investments with long operational lives, in some cases 100 years or more (Hallegatte et al., 2011a). In low- and most middle-income cities, very large additional investment is needed to address deficits in infrastructure and services; without this investment, making the short- to long-term trade-off to improve resilience is difficult (Dodman and Satterthwaite, 2009). This is an opportunity for "climate smart" infrastructure planning that considers how to combine pro-poor development and climate change adaptation and mitigation. This is a more difficult task for cities such as New York with dense aging infrastructure and materials that "may not be able to withstand the projected strains and stresses from a changing climate" (Zimmerman and Faris, 2010, p. 63). These cities also have the opportunity, when replacing aging infrastructure, to integrate climate considerations into the new infrastructure decision-making processes.

8.2.4.1. Water Supply, Wastewater, and Sanitation

Water and sanitation systems affect household well-being and health, as well as influencing urban economic activities, energy demands, and the rural-urban water balance (Gober, 2010). Climate change will impact residential water demand and supply and its management (O'Hara and Georgakakos, 2008). Among the projected impacts are altered precipitation and runoff patterns in cities, sea level rise and resulting saline ingress, constraints in water availability and quality, and heightened uncertainty in long-term planning and investment in water and waste water systems (Muller, 2007; Fane and Turner, 2010; Major et al., 2011). Local government departments and utilities responsible for water supply and waste water management must confront these new climatic patterns and major uncertainties in availabilities and learn to respond to dynamic and evolving sets of constraints (Milly et al., 2008).

Climate change will increase the risk and vulnerability of urban populations to reductions in groundwater and aquifer quality (e.g., Praskievicz and Chang, 2009; Taylor and Stefan, 2009), subsidence, and increased salinity intrusion. High levels of groundwater extraction have led to serious subsidence problems in cities such as Bangkok (Babel et al., 2006) and Mexico City (Romero-Lankao, 2010), which damage buildings, fracture pipes, and can increase flood risks (see also Jha et al., 2012). This problem can be compounded in coastal cities when saline intrusion reduces groundwater quality and erodes structures.

In many rapidly developing cities, the impact of climate change on water supplies will interact with growing population, growing demand, and economic pressures, potentially heightening water stress and negative impacts on the natural resource base, with effects for water quality and quantity. Caribbean nations, for example, with their expanding middle-class urban population, face sharply raised demands for water and the associated challenges of managing runoff, storm water, and solid wastes. Projected reductions in rainfall amounts at specific times in particular locations would aggravate such water stresses (Cashman et al., 2010). In Shanghai, climate change is expected to bring decreased water availability as well as flooding, groundwater salinization, and coastal subsidence. The city's population of 17 million is projected to continue expanding, often within areas that are "likely increasingly flood-prone" (de Sherbinin et al., 2007, p. 60). Groundwater depletion has contributed to land subsidence in these already vulnerable areas, reinforcing the water stresses and risks of erosion (de Sherbinin et al., 2007). In several large Andean cities, including Lima, La Paz, and Quito, declining volumes of glacial melt water have been observed, with expected further declines (Buytaert et al., 2010; Chevallier et al., 2011).

Several studies estimate how climate change will alter relationships among water users, exacerbating tensions and conflicts between the various end users (residential, commercial, industrial, agricultural, and infrastructural) (Roy et al., 2012; Tidwell et al., 2012). In small and mid-sized African cities, the effect of flooding on well water quality is a growing concern (Cissé et al., 2011). Floods, droughts, and heavy rainfall have also impacted agriculture and urban food sources, and can exacerbate food and water scarcity in urban areas (Gasper et al., 2011). But not all water systems are projected to experience negative impacts. Chicago's Metropolitan Water Reclamation District (MWRD) found that reduced precipitation due to climate change would decrease pumping and general operations costs, as sewers will contain less rainwater in drier seasons (Hayhoe et al., 2010).

Wastewater and sanitation systems will be increasingly overburdened during extreme precipitation events if attention is not paid to maintenance, the limited capacity of drainage systems in old cities, or lack of provision for drainage in most unplanned settlements and in many urban centers (Wong and Brown, 2009; Howard et al., 2010; Mitlin and Satterthwaite, 2013). In the city of La Ceiba, Honduras, stakeholders concluded that urban drainage and improved management of the Rio Cangrejal watershed were top priorities for protection against projected climate change impacts; the city lacks a stormwater drainage system but experiences regular flooding (Smith et al., 2011).

Flooding is often made worse by uncontrolled city development that builds over natural drainage channels and flood plains or by a failure

to maintain drainage channels (often blocked by solid wastes where waste collection is inadequate). These problems are most evident in cities where there are no drains or sewers to help cope with heavy precipitation (Douglas et al., 2008) and no service to collect solid wastes (in many cities in low-income nations, less than half the population has regular solid waste collection; see Hoornweg and Bhada-Tata, 2012). Many cities in high-income nations also face challenges. An analysis of three cities in Washington State, assessing future streamflows and peak discharges, concluded that "concern over present (drainage) design standards is warranted" (Rosenberg et al., 2010, p. 347). Climate change was identified as a key driver affecting Britain's future sewer systems. According to the model used, the volume of sewage released to the environment by combined sewage overflow spills and flooding was projected to increase by 40% (Tait et al., 2008).

8.2.4.2. Energy Supply

Energy exerts a major influence on economic development, health, and quality of life. Any climate change-related disruption or unreliability in power or fuel supplies can have far-reaching consequences, affecting urban businesses, infrastructure, services (including healthcare and emergency services) and residents, as well as water treatment and supply, rail-based public transport, and road traffic management (Jollands et al., 2007; Finland Safety Investigations Authority, 2011; Halsnæs and Garg, 2011; Hammer et al., 2011).

Past experiences with power outages indicate some of the knock-on effects (Chang et al., 2007). New York City's blackout of 2003 lasted 28 hours and halted mass transport, surface vehicles due to signaling outages, and water supply (Rosenzweig and Solecki, 2010). A review of climate change impacts on the electricity sector (Mideksa and Kallbekken, 2010) projects reductions in the efficiency of water cooling for large electricity-generating facilities, changes in hydropower and wind power potential, and changing demand for heating or cooling in the USA and Europe. Low-income households in Chittagong use candles or kerosene lamps during frequent power outages; this was found to disturb children's studies, increase expenses, and overheat homes (Rahman et al., 2010).

Climate change will alter patterns of urban energy consumption, particularly with respect to the energy needed for cooling or heating (for a review, see Mideksa and Kallbekken, 2010). Climate change will bring increases in air conditioning demand and in turn heightened electricity demand (Radhi, 2009; see also Hayhoe et al., 2010, for a discussion of this in relation to Chicago). In temperate and more northern regions, winter temperature increases may decrease energy demand (Mideksa and Kallbekken, 2010). In most cases within individual cities, potential increases in summertime electricity demand from climate change will exceed reductions in winter energy demand reductions (Hammer et al., 2011). Less is known about the demand-side impacts in low- and lower-middle-income nations, where large sections of the urban population still lack access to electricity (Johansson et al., 2012; Satterthwaite and Sverdlik, 2012). Most of these nations are expected, as noted, to have increased mean temperatures or rising frequency of heat waves (IPCC, 2007).

Many cities' economies will be affected if water scarcity and variability interrupt hydropower supplies. For instance, reductions in hydroelectric generation will have impacts on the economies of many urban centers in Brazil as well as in neighboring countries (de Lucena et al., 2009, 2010; Schaeffer et al., 2011). Cities in sub-Saharan Africa often rely on hydropower for their electricity, and failures in supplies can lead "to a more general 'urban failure'" (Muller, 2007, p. 106). Laube et al. (2006) discuss water shortages in Ghana following low precipitation periods, and the potential for competition between hydropower and water provision, including to downstream urban centers. Declining water levels in the Hoover Dam have raised the possibility that Los Angeles will lose a major power source, and that Las Vegas will face a severe decline in drinking water availability (Gober, 2010).

Summer heat waves, with spikes in demand for air conditioning, can result in brownouts or blackouts (Mirasgedis et al., 2007; Mideksa and Kallbekken, 2010). Cities in the temperate regions of Australia already experience regular blackouts on hot summer days, largely due to residential air-conditioner use (Maller and Strengers, 2011). Research in Boston suggested that rising energy demands in hotter summers have meant a "disproportional impact on (the) elderly and poor, increased energy expenditures; loss of productivity and quality of life" (Kirshen et al., 2008, p. 241). Any increase in the frequency or intensity of storms may disrupt electricity distribution systems because of the collapse of power lines and other infrastructure (Rosenzweig et al., 2011; see also Chapter 10).

8.2.4.3. Transportation and Telecommunications

Climate change-related extreme events will affect urban transportation and telecommunication infrastructure, including a variety of capital stock, such as bridges and tunnels, roads, railways, pipelines, and port facilities, data sensors, and wire and wireless networks (Koetse and Rietveld, 2009; Hallegatte et al., 2011a; Jacob et al., 2011; Major et al., 2011). In the Gulf Coast region of the United States, 27% of major roads, 9% of rail lines, and 72% of ports are at or below 122 cm (4 ft) in elevation. With a storm surge of 7 m (23 ft), more than half the area's major highways, almost half the rail miles, 29 airports, and virtually all the ports are subject to flooding (Savonis et al., 2008). Assessing possible disruptions of transport networks within cities and urban systems is critical. Loss of telecommunication access during extreme weather events can inhibit disaster response and recovery efforts because of its critical role in providing logistical support for such activity (Jacob et al., 2011).

Ports are central to international trade and climate change poses substantial challenges related to exposed locations in coastal zones, low-lying areas, and deltas; long lifespans of key infrastructure and interdependencies with trade, shipping, and inland transport services that are also vulnerable (Oh and Reuveny, 2010; Asariotis and Benamara, 2012). Hurricane Sandy crippled the New York region, leading to a week-long shut-down of one of the largest container ports in the USA (Hallegatte et al., 2013).

Large sections of the urban population in low- and middle-income nations live in settlements without all-weather roads and paths that allow for emergency vehicle access and rapid evacuation. For instance, in Chittagong, Bangladesh, extremely narrow roads limit emergency access

to most informal neighborhoods, exacerbating health and fire risks (Rahman et al., 2010). In Lagos's informal settlements, a 2006 resident survey ranked roads second to drainage in terms of needed facilities (Adelekan, 2010). Evacuations in low-income areas may also be hampered by hazardous locations, absence of public transport, and inadequate governance. Following the 2003 and 2006 floods in Santa Fe, Argentina, the lack of information and official evacuation mechanisms prevented timely responses; some residents also chose to stay in their homes to protect their possessions from looters (Hardoy and Pandiella, 2009).

Low-income urban residents can also be profoundly affected during and after extreme weather events that damage critical public transit links, prevent access to work, and heighten exposure to health risks. Interviews in Georgetown, Guyana, found that the limited transport access of low-income households during floods made them more prone to losing time from work or school, compared to wealthier households. Poorer households rarely owned cars, and wading barefoot through floodwaters exposed them to water-borne pathogens (Linnekamp et al., 2011). Some studies find urban women walk or use public transport more than men (World Bank, 2010c); hence, the gendered impact of transport disruptions may merit greater consideration (UN-HABITAT, 2011a; Levy, 2013).

The literature on urban transport and climate change focuses more on mitigation, with less attention to vulnerability, impacts, and adaptation (Hunt and Watkiss, 2011). Existing studies on impacts are often limited to the short-term demand side, particularly in passenger transport (Koetse and Rietveld, 2009). However, climate change creates several challenges for transport systems. The daily functioning of most transport systems is already sensitive to fluctuations in precipitation, temperature, winds, visibility, and for coastal cities, rising sea levels with the associated risks of flooding and damages (Love et al., 2010). Transport is highly vulnerable to climate variability and change, and the economic importance of transport systems has increased with the rise of just-in-time delivery methods, heightening the risk of losses due to extreme weather (Gasper et al., 2011).

In addition to adapting road transport, cities should ensure bridges, railway cuttings, and other hard infrastructure is resilient to climate change over their service lifespan (Jaroszweski et al., 2010). Few studies have examined the effects of climate change on railways, but rail system failures are known to be related to high temperatures, icing, and storms (Koetse and Rietveld, 2009; see Dobney et al., 2008, for future heat-related delays in UK railways; also Palin et al., 2013, offers a broad discussion of climate change effects on the UK rail network). Very few studies have examined the vulnerability of air- and sea-borne transport and infrastructure, but climate change could mean more and lengthier weather-related delays and disruption (Eurocontrol, 2008; Becker et al., 2012).

Loss of sea ice can benefit some cities by increasing opportunities for developing road networks or ports. However, it may be costly to adapt road, air, and water transport networks to the known environmental risks associated with such redevelopment (Larsen et al., 2008). For industries and communities in northern Canada, reduced freshwater-ice levels creates longer shipping seasons and could also promote new seaports in marine environments. But thawing of permafrost can also result in instability and major damage to roads, infrastructure, and buildings in and around northern cities and towns, and inland towns will require sizable investments to replace winter ice roads with land-based roads (Prowse et al., 2009).

The direct impacts of extreme weather on transport are more easily assessed than the indirect impacts or possible knock-on effects between systems. Studies have often examined the direct impacts of flooding on transport infrastructure, but the indirect costs of delays, detours, and trip cancellation may also be substantial (Koetse and Rietveld, 2009). Mumbai's 2005 floods caused injuries, deaths, and property damage but also serious indirect impacts as most city services were shut down without contact via rail, road, or air (Revi, 2005). Transport and other urban infrastructure networks are often interdependent and located in close proximity to one another, yet only a few assessments have considered the joint impacts (Kirshen et al., 2008; Hayhoe et al., 2010).

Transportation systems are critical for effective disaster response—for example, where populations have to be evacuated prior to an approaching storm or where provision is urgently needed for food, water, and emergency services to affected populations.

Key elements in cities' communications systems may have to be strengthened—for instance, to avoid masts toppling due to strong winds and electrical support facilities that need to be moved or protected against flooding (Zimmerman and Faris, 2010, p. 74). New York City's dispersed communications network faces several climate-related risks. Electrical support facilities can be flooded; cell phone towers can topple in strong winds or become corroded as sea levels rise (Zimmerman and Faris, 2010). In Alaska, telecommunications towers are settling as a result of warming permafrost (Larsen et al., 2008). Emergencies may generate a demand for communications that exceeds systems' capacities. During the extreme rainfall event in 2005, Mumbai's telecommunications networks ceased to function due to a mix of overload, shut down of the power system, and lack of diesel supplies for generators (Revi, 2005).

8.2.4.4. Built Environment, and Recreation and Heritage Sites

Housing ideally provides its occupants with a comfortable, healthy, and secure living environment and protects them from injuries, losses, damage, and displacement (Haines et al., 2013). For many low-income households, livelihoods also depend on home-based enterprises, and housing is key to protecting their assets and preventing disruption of their incomes. Decent housing has particular importance for vulnerable groups, including infants and young children (Bartlett, 2008), older residents, or those with disabilities or chronic health conditions.

Urban housing is often the major part of the infrastructure affected by disasters, according to Jacobs and Williams (2011). Extreme events such as cyclones and floods inflict a heavy toll, particularly on structures built with informal building materials and outside of safety standards (UNISDR, 2011). Dhaka's 1998 floods damaged 30 percent of the city's units; of these, more than two-thirds were owned by the lower-middle

classes and the poorest (Alam and Rabbani, 2007). Adelekan (2012) shows that a relatively modest increase in wind speeds during storms caused widespread damage in central Ibadan. Relative to the preceding decade, the period from 1998 to 2008 showed higher mean maximum wind gusts and more frequent windstorms with peak gusts greater than 48 knots, and the impacts were severe in part because of the high concentration of residents in damaged buildings. Increased climate variability, warmer temperatures, precipitation shifts, and increased humidity will accelerate the deterioration and weathering of stone and metal structures in many cities (Grossi et al., 2007; Thornbush and Viles, 2007; Smith et al., 2008; Bonazza et al., 2009; Stewart et al., 2011).

Recreational sites such as parks and playgrounds will also be affected. In New York City, these are defined as critical infrastructure and are often located in low elevation areas subject to storm surge flooding (Rosenzweig and Solecki, 2010). Little research has examined the effects on urban tourism in particular (Gasper et al., 2011).

The increased risks that climate change brings to the built environment (Spennemann and Look, 1998; Wilby, 2007) also apply to built heritage. This has led to the Venice Declaration on Building Resilience at the Local Level Towards Protected Cultural Heritage and Climate Change Adaptation Strategies, which brings together UNESCO, UN-HABITAT, EC, and individual city mayors. An example is Saint-Louis in Senegal, a coastal city and World Heritage Site on the mouth of the Senegal river, which has frequent floods and large areas at risk from river and coastal flooding. There are initiatives to reduce flooding risks and relocate families from locations most at risk, but the local authority has very limited investment capacity (Diagne, 2007; Silver et al., 2013).

8.2.4.5. Green Infrastructure and Ecosystem Services

Climate change will alter ecosystem functions affected by changes in temperature and precipitation regimes, evaporation, humidity, soil moisture levels, vegetation growth rates (and allergen levels), water tables and aquifer levels, and air quality. It will also accentuate the value of ecosystems services and green infrastructure for adaptation. "Green infrastructure" refers to interventions to preserve the functionality of existing green landscapes (including parks, forests, wetlands, or green belts), and to transform the built environment through phytoremediation and water management techniques and by introducing productive landscapes (Foster et al., 2011b; La Greca et al., 2011; Zhang et al., 2011). These can influence the effectiveness of pervious surfaces used in storm water management, green/white/blue roofs, coastal marshes used for flood protection, urban agriculture, and overall biomass production. Mombasa will experience more variable rainfall as a result of climate change, making the expansion of green infrastructure more difficult (Kithiia and Lyth, 2011). Trees in British cities will be increasingly prone to heat stress and attacks by pests, including new non-native pathogens and pests that can survive under warmer or wetter conditions (Tubby and Webber, 2010). Urban coastal wetlands will be inundated with sea level rise. In New York City, remnant coastal wetlands will be lost to sea level rise because bulk heading and intensive coastal development will prevent their natural movement inland (Gaffin et al., 2012).

8.2.4.6. Health and Social Services

The effects of climate change will also be evident across urban public services including health and social care provision, education, police, and emergency services (Barata et al., 2011, see also Chapter 11). Most urban centers in low-income nations and many in middle-income nations lack adequate social and public service provision (Bartlett, 2008; UN-HABITAT, 2003a) while higher-income cities are only beginning to consider climate change in their health or disaster management plans (Brody et al., 2010).

Although there are few studies on adapting education, police, or other key services, a growing public health literature has discussed multi-sectoral adaptation strategies (Huang et al., 2011). Cities' existing public health measures provide a foundation for adapting to climate change, such as heat warning systems or disease surveillance (McMichael et al., 2008; Bedsworth, 2009). Negative climate impacts have been highlighted on some of the most vulnerable in society—including children (Ebi and Paulson, 2010; Sheffield and Landrigan, 2011; Watt and Chamberlain, 2011), the elderly (White-Newsome et al., 2011; Oven et al., 2012), and the severely disadvantaged (Ramin and Svoboda, 2009; see also Chapter 11).

8.2.5. Urban Transition to Resilience and Sustainability

The question of how to promote increased resilience and enhanced sustainability in urban areas (as illustrated in Table 8-2) has become a central research topic and policy consideration. It is well recognized that climate change risks affect this process by heightening uncertainties and altering longstanding patterns of environmental risk in cities, many of which continue to face other significant stressors such as rapid population growth, increased pollution, resource demands, and concentrated poverty (Wilbanks and Kates, 2010; Mehrotra et al., 2011a). This section discusses how climate change increasingly affects municipal decision-making frames and alters local conceptions of cities as vehicles for economic growth, for political change, for meeting livelihoods and basic needs, as well as larger-scale goals of resilience and sustainability.

In recent years, different models of urban environmental transition have been introduced to illustrate the connections between health hazards and environmental impacts as cities and neighborhoods develop—for example, shifts from a "sanitary city" focused on public health and basic service provision to a "sustainable city" focused on long-term planning, resource efficiency, and ecosystem services (McGranahan, 2007). The latter includes consideration of a city's use of global and local sinks for wastes that lie outside its boundaries (McGranahan, 2007; Wilson, 2012). Within these models, key variables have been identified that make cities vulnerable to climate change (e.g., extensive infrastructure networks, high-density population in exposed or other sensitive sites).

There is the opportunity to promote societal transition that enhances resiliency and adaptive capacity in the face of accelerated climate change (Gusdorf et al., 2008; Ernstson et al., 2010; Mdluli and Vogel, 2010; Tompkins et al., 2010; Pelling and Manuel-Navarrete, 2011; Pelling, 2011a). Transition in this context can take place at a broad

Table 8-3 | Urban areas: Current and indicative future climate risks. Key risks are identified based on an assessment of the literature and expert judgments by Chapter 8 authors, with the evaluation of evidence and agreement presented in supporting chapter sections. Each key risk is characterized as very low to very high. For the near-term era of committed climate change (2030–2040), projected levels of global mean temperature increase do not diverge substantially across emission scenarios. For the longer-term era of climate options (2080–2100), risk levels are presented for global mean temperature increases of 2°C and 4°C above pre-industrial levels. For each time frame, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adapted state.

Climate-related drivers of impacts: Warming trend; Extreme temperature; Drying trend; Extreme precipitation; Snow cover; Damaging cyclone; Sea level; Ocean acidification; Flooding

Level of risk & potential for adaptation: Potential for additional adaptation to reduce risk; Risk level with **high** adaptation; Risk level with **current** adaptation

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation (Very low / Medium / Very high)
Modal urban (*medium confidence*) [8.2, 8.3, 8.4]	Climate change will have profound impacts on urban infrastructure systems and services, the built environment, and ecosystem services and hence on urban economies and populations. This could exacerbate existing social, economic, and environmental drivers of risk, especially for vulnerable groups who lack essential services. An appropriate urban governance frame and coordinated urban adaptation focused on the built environment, improved infrastructure, and services and risk reduction has significant potential for reducing key climate risks in the medium term and especially in the long term.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	
Coastal zone systems (*medium confidence*) [8.2, 8.3]	Coastal cities with extensive port facilities and large-scale industries are vulnerable to increased flood exposure. High-growth cities located on low-lying coastal areas are also at greater risk. There is a possibility of nonlinear increase in coastal vulnerability over the next two decades.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	
Terrestrial ecosystems and ecological infrastructure (*medium confidence*) [8.2, 8.3]	Ecosystem services will be impacted by altered ecosystem functions such as temperature and precipitation regimes, evaporation, humidity, and soil moisture levels, indicating close links with sustainable water management. Knowledge gaps exist with respect to thresholds to adaptation of various ecosystems.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	
Water supply systems (*high confidence*) [8.2, 8.3]	Adaptation response requires changes to network infrastructure as well as demand side management, to ensure sufficient water supplies, increased capacities to manage reduced freshwater availability, flood risk reduction, and water quality.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	
Waste water system (*high confidence*) [8.2, 8.3, 8.4]	Managing waste water flows improves water supply and ecosystem services. Reducing vulnerability of infrastructure may be easier in new areas, well-funded local bodies, or as part of scheduled interventions.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	
Green built infrastructure (*medium confidence*) [8.3]	Green infrastructure not utilized sufficiently in most cities. Climate change impacts can bring attention to the dual benefits of green infrastructure for climate change mitigation and impact management.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	
Energy systems (*high confidence*) [8.2, 8.4]	Most urban centers are energy intensive, with energy-related climate policies focused only on mitigation measures. A few cities have adaptation initiatives underway for critical energy systems. There is great potential for non-adapted, centralized energy systems to magnify and cascade impacts to national or transboundary consequences from localized extreme events.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	

Continued next page →

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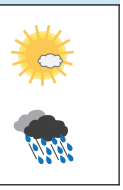
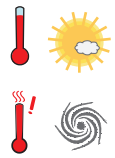
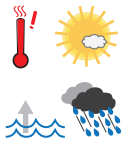
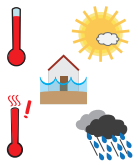
Table 8-3 (continued)

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Food systems and security (*high confidence*) [8.2, 8.3]	Urban food sources are dependent on local, regional, and often global 8.2, 8.3 supplies. Climatic drivers can exacerbate food insecurity, especially of the urban poor. Enhanced social safety nets can support adaptation measures. Urban and peri-urban agriculture, local markets, and green roofs hold good prospects as adaptive measures, but are under-utilised in rapidly growing cities.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Transportation systems (*medium confidence*) [8.2, 8.3]	A difficult sector to adapt due to large existing stock, especially in developed country cities, leading to potentially large secondary economic impacts with regional and potentially global consequences for trade and business. Emergency response requires well-functioning transport infrastructure.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Communication systems (*medium confidence*) [8.2, 8.3]	Resilient communication systems are a critical component of emergency response, and therefore adaptation. The rise of decentralized and networked mobile communications offers great potential for real-time and easily accessed information dissemination and communication systems. Information quality control is a key element in realizing the potential of communications systems for early warning and adaptation.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Urban risks associated with housing (*high confidence*) [8.3]	Poor quality, inappropriately located housing is often most vulnerable to extreme events. Adaptation options include enforcement of building regulations and upgrading. Some city studies show the potential to adapt housing and promote mitigation, adaptation, and development goals simultaneously. Rapidly growing cities, or those rebuilding after a disaster, especially have opportunities to increase resilience, but this is rarely realized. Without adaptation, risks of economic losses from extreme events are substantial in cities with high-value infrastructure and housing assets, with broader economic effects possible.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Human health (*high confidence*) [8.2, 8.3, 8.4]	Health is a higher order risk impacted by key developmental issues including water supply, water and air quality, waste management, housing quality, sanitation, food security, and provision of health care services and insurance. Certain groups of people are particularly vulnerable, such as the elderly, the chronically ill, the poor, and the very young, and require targeted social care interventions. Longer term developmental improvements need considerable financial resources and coherent intergovernmental action, limiting prospects for near-term adaptation.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Human security and emergency response (*medium confidence*) [8.3, 8.4]	Security is linked to key developmental issues such as income, housing, health care, education, and food security. Moderate prospects as city governments can enhance emergency response services, to significantly reduce vulnerability for those who are most at risk. Where security and emergency forces have limited public trust, and especially with regard to gender issues, scope for supporting adaptation and risk management is considerably constrained.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Key economic sectors and services (*medium confidence*) [8.2, 8.3]	Large diversity across cities in terms of key economic sectors and adaptive capacity to disruptions in city services. Cities reliant on climate-sensitive tourism or agriculture may require economic diversification. Good prospects for advancing co-benefits through "green" and "waste" economy.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Livelihoods (*medium confidence*) [8.3]	Informal economy is more vulnerable, and often less adaptive in the short term. Social protection measures, in the specific context of urban livelihoods, are required.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Poverty and access to basic services (*high confidence*) [8.3]	Reducing basic service deficit could reduce hazard exposure, especially of the poor and vulnerable, alongside upgrading of informal settlements, improved housing conditions and enabling the agency of low-income communities. Significant prospects where adaptation is already being implemented as part of human development or social protection.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high

scale, but can also often occur with incremental changes, potentially precipitating regime level shifts (Pelling and Manuel-Navarrete, 2011). Although such shifts also can happen as a result of discrete regime failure (Pelling, 2011a), this is less common. Such transformational changes have been observed in a variety of urban disaster contexts. Most often they follow urban earthquake events (e.g., in Nicaragua, Guatemala, Turkey) but are also associated with flooding in Bangladesh (Pelling, 2011a). Disasters can enable regime level change at moments in history where competing approaches to development have political voice, an organizational base that articulates competing analysis of the causes of the disaster, and weak systemic counter response (Pelling, 2001a).

Climate change may exacerbate existing social and economic stressors in cities with the potential to affect urban livelihoods, engender political or social upheaval, or generate other negative impacts upon human security (Bunce et al., 2010; Siddiqi, 2011; Simon and Leck, 2010; see Chapters 22-30 for more detail). Climate change could potentially contribute to violent conflicts and spur migration from highly vulnerable sites in cities or increasingly environmentally stressed locales (Reuveny, 2007; Adamo, 2010; de Sherbinin et al., 2011). But there is considerable uncertainty regarding projections.

Migration may represent an important household strategy to adapt by diversifying income sources and livelihoods (Tacoli, 2009). Although climate change can significantly disrupt livelihoods, outcomes will depend on particular social structures, state institutions, and other broader determinants of human security (Barnett and Adger, 2007). In sum, "dwindling resources in an uncertain political, economic and social context are capable of generating conflict and instability, and the causal mechanisms are often indirect" between climate and conflict (Beniston, 2010, p. 567).

Different management solutions to climate change also have implications for equity (Pelling et al., 2012). For example, the privatization of urban water supply and sanitation systems can advantage specific groups over others. Conversely, community-based solutions that also build social capital can be a component in generating urban resilience. However, even these solutions may exacerbate inequality at the city level, with only those local areas with strong levels of social capital being able to benefit most from community led action or garner support from international and national partners (UN-HABITAT, 2007; Pelling et al., 2012).

Table 8-3 serves as the link between Section 8.2 (which focuses on climate change risks and impacts) and Section 8.3 (which focuses on adaptation). It summarizes key risks from climate change to urban areas and the potential to reduce risk through adaptation for the present, near term (2030–2040), and long term (2080–2100). Table 8-6 has comparable summaries of key risks and potential for adaptation for Dar es Salaam, Durban, London, and New York City. For the long term, under a global mean temperature increase of 2°C above preindustrial levels, many key risks increase from the near term. High adaptation can reduce these risk levels, although for most key risks not as much as high adaptation in the near term. For the long term under a temperature increase of 4°C above preindustrial levels, almost all key risks are "very high" and with many of them remain very high with high adaptation.

8.3. Adapting Urban Areas

8.3.1. Introduction

Since the Fourth Assessment Report, the literature on urban climate change adaptation has increased significantly, especially in three aspects:

- The examination of risks and vulnerabilities for particular cities
- The definition of "resilience" and identification of opportunities to strengthen resilience at all scales
- Documentation produced by or for particular city governments on adaptation.

There is less on local government decisions to include adaptation in plans and investment programs, but see Solecki (2012) and Roberts (2008, 2010) for exceptions. As described below, studies have also examined how to link adaptation and city development plans and adaptation measures for key sectors.

It has been suggested that "the complexities and uncertainties associated with climate change pose by far the greatest challenges that planners have ever been asked to handle" (Susskind, 2010, p. 219). Municipal and higher-level adaptation plans will need to take into account uncertainty about future climates and extremes. These will need to consider direct and indirect economic costs, including the trade-off of inaction and locking into ill-adapted infrastructure versus investment in adaptation when climate change is less than anticipated (Hallegatte et al., 2007a). Several U.S. studies have considered the cost on inaction for specific states (Niemi et al., 2009a,b,c; Repetto, 2011a,b, 2012a,b,c,d; Backus et al., 2012; Wilbanks et al., 2012).

While local governments are the fulcrum of urban adaptation planning, challenges include inadequate resources and technical capacities and a lack of data on climate-related risks and vulnerabilities. Existing climate models are not downscaled to the city level. Data on climate change risks are infrequently collected and often fragmented across city government departments (Hardoy and Pandiella, 2009). Many proposed adaptation measures respond to specific local or regional hazard risks that may not be directly climate related (Bulkeley, 2010). To encourage local dialog in adaptation planning, urban climate data need to be integrated geographically, across time scales, and consider the range of regional benefits and costs of climate policy (Ruth, 2010).

8.3.2. Development Plans and Pathways

As AR4 emphasized, many of the forces shaping greenhouse gas emissions also underlie development pathways—including the scale, nature, and location of investment in infrastructure (Wilbanks et al., 2007). These influence the form and geography of urban development as well as the scale and location of climate-related risks to urban buildings, enterprises, and populations. Local, provincial, and national governments share responsibility for encouraging new investments and migration flows away from high-risk sites through climate-sensitive disaster risk management, urban planning, and zoning and infrastructure investments. But the priority given to economic growth usually means this is rarely implemented with vigor (Douglass, 2002; Reed et al., 2013).

8.3.2.1. Adaptation and Development Planning

Urban adaptation is becoming important to some national and regional governments and many city governments. In high-income countries, interactions and division of responsibility between national and local level have been examined (see, e.g., Massetti et al., 2007, for Italy and Juhola and Westerhoff, 2011, for Italy and Finland); also local adaptation implementation through subsidies and flexible schemes in different contexts and the transfer of authority and resources to the city level (for the Netherlands; see Gupta et al., 2007). New decision making strategies for local governments consider the complexity and dynamics of evolving socio-ecological systems (Kennedy et al., 2011), for instance, adaptation plans and responses in Sydney to cope with sea level rise and storms (Hebert and Taplin, 2006) and adaptation planning in California (Bedsworth and Hanak, 2010).

The literature on urban adaptation in low- and middle-income nations has grown since AR4 (see Box 8-1 for publications since 2007). A 2011 review (Hunt and Watkiss, 2011) could draw on eight case studies in Asia, five in Africa, four in South America, as well as cases from Europe, Northern America, and Australasia.

Four issues can be highlighted around urban adaptation:

- Low- and middle-income nations have most of the world's current and future urban population.
- Key development issues of poverty and social inequality may be aggravated by climate change.
- Human agency among low-income inhabitants and organizations is important in building local responses.
- Well-functioning multilevel governance helps in developing adaptation strategies (Sánchez-Rodríguez, 2009).

Although few publications suggest specific operational strategies, they do stress the importance of the link between climate adaptation and development—urban infrastructure and other development deficits can contribute to adaptation deficits. Manuel-Navarrete et al. (2011) explore this interplay in the Mexican Caribbean, where hurricane exposure and vulnerability are influenced by political decisions and contingent development paths. Few reports exist on multidimensional approaches to operational adaptation. There are some examples of adaptation integrated with development interventions and addressing structural drivers of social and urban vulnerability—for instance, Climate Action Plans of Mexico City, Cartagena, and San Andrés de Tumaco (Sánchez-Rodríguez, 2009).

Despite growing acceptance of its importance, there are reasons for the general lack of attention to urban adaptation. First, national climate change policies usually give little attention to urban adaptation compared to sectors like agriculture. The ministries or agencies responsible for these policies often have little involvement in urban and little influence on those whose cooperation is essential, for example, for social policies, public works, and local government (Hardoy and Pandiella, 2007; Ojima, 2009; Roberts, 2010). Social policies and priorities influence the social and spatial distribution of climate-related risk and vulnerability—for instance, provision for health care, emergency services, and safety nets—yet few agencies recognize their potential role in reducing risk and vulnerability.

A second factor is the initial focus for many cities on mitigation rather than adaptation (with commitments made to lowering GHG emissions), in part because of the focus of international support. Local decision makers frequently view climate change as a marginal issue, but adaptation usually ranks lower than mitigation on the agenda (Bulkeley, 2010; Simon, 2010). Mexico City focuses on mitigation, but adaptation is still a vague concept (GDF, 2006, 2008) seen more, for instance, as a capacity to cope with floods through early warning systems than through comprehensive, long-term measures such as watershed management to reduce the speed and volume of flood waters. There is still little

Box 8-1 | Recent Literature on Urban Adaptation in Low- and Middle-Income Nations

Among the papers and books considering climate change adaptation in urban areas since 2007 are those on Cape Town (Mukheibir and Ziervogel, 2007; Ziervogel et al., 2010; Cartwright et al., 2012), Durban (Roberts, 2008, 2010; Roberts et al., 2012; Cartwright et al., 2013; Roberts and O'Donoghue, 2013), and other urban centers in Africa (Douglas et al., 2008; Wang et al., 2009; Lwasa, 2010; Kithiia and Lyth, 2011; World Bank, 2011; Adelekan, 2012; Castán Broto et al., 2013; Kiunsi, 2013; Silver et al., 2013); urban centers in Bangladesh (Alam and Rabbani, 2007; Jabeen et al., 2010; Banks et al., 2011; Haque et al., 2012; Roy et al., 2013); India (Revi, 2008; Sharma and Tomar, 2010; Saroch et al., 2011); Pakistan (Khan et al., 2008); Philippines (Button et al., 2013); and Latin America (Romero-Lankao, 2007, 2010; Hardoy and Pandiella, 2009; Hardoy and Romero-Lankao, 2011; Hardoy and Ruete, 2013; Hardoy and Velasquez Barrero, 2013; Luque et al., 2013). In China, discussions of division of responsibility between national and local levels include Teng and Gu (2007), Liu and Deng (2011), and Li (2013).

Other papers or books discussing urban adaptation in low- and middle-income nations include de Sherbinin et al. (2007), McGranahan et al. (2007), Agrawala and van Aalst (2008), Bartlett (2008), Kovats and Akhtar (2008), Ayers (2009), Bicknell et al. (2009), Tanner et al. (2009), Rosenzweig et al. (2011), Moser et al. (2010), World Bank (2010b), Manuel-Navarrete et al. (2011), Moench et al. (2011), UN-HABITAT (2011a), Bulkeley and Castan Broto (2013), and Bulkeley and Tuts (2013).

literature on adaptation for Brazilian cities (Ojima, 2009; Soares, 2009). In Sao Paulo, adaptation is limited to broad declarations about necessary actions, even as the city gets hit by floods, landslides, and water scarcity (Puppim de Oliveira, 2009; Nobre et al., 2010; Martins and da Costa Ferreira, 2011). The pressure on national and local governments to act is lessened by the scant public awareness of the importance of climate change adaptation (Nagy et al., 2007), and a "knowledge gap" between policy makers and scientists (Sánchez-Rodríguez, 2011). However, as Section 8.4 describes, interest in urban adaptation is growing, encouraged by the increasing engagement of transnational municipal networks and donor agencies (Bulkeley, 2013).

8.3.2.2. Disaster Risk Reduction and Its Contribution to Climate Change Adaptation

The growing concentration of people and activities in urban centers and the increasing number and scale of cities can generate new patterns of disaster hazard, exposure and vulnerability, as evident in the rising number of localized disasters in urban areas in many low- and middle-income nations associated with extreme weather (storms, flooding, fires, and landslides) (Douglas et al., 2008; UNISDR, 2009, 2011). This is relevant to climate change adaptation, given the increasing frequency and intensity of potentially hazardous weather events associated with climate change. Extreme weather events have also helped raise awareness of citizens and local governments of local risks and vulnerabilities.

Exposure to weather-related risk in growing urban areas increases when local governments fail to address their responsibilities by expanding or upgrading infrastructure and services and reducing risk through building standards and appropriate land use management (UNISDR, 2009, 2011). This is typical in countries with low per capita GDPs and weak local governance (i.e., in the first two categories of Table 8-2), and can be exacerbated by rapid urban population growth. Urbanization accompanied by more capable and accountable local governments can reduce disaster risk, as evident in the declines in mortality from extreme weather (and other) disasters in many middle- and all high-income nations (UNISDR, 2011). The most urbanized nations generally have the lowest mortality to these events (UNISDR, 2009).

Local government investment is usually a small proportion of total investment in and around an urban center, but has particular importance in risk reduction. Urban governments have explicit responsibilities for many assets that may be risk prone, often including schools, hospitals, clinics, water supplies, sanitation and drainage, communications, and local roads and bridges (IFRC, 2010).

Even where private provision for these assets is significant, local government usually coordinates such provision and has a significant planning and regulation role, ensuring buildings and infrastructure meet needed standards and guiding development away from high-risk areas.

From the late 1980s, some Latin American cities took a new approach to disaster risk, involving three processes:

- Detailed analyses of local disaster records, including smaller events than those in international databases
- Recognition that most disasters were the result of local failures to assess and act on risk
- Recognition of the central roles of local governments in disaster risk reduction, supported national and local civil defense organizations, working with civil society and settlements most at risk (UNISDR, 2009; IFRC, 2010).

This led to institutional and legislative changes at national or regional level (Gavidia, 2006; IFRC, 2010). In Colombia, a national law supports disaster risk reduction and a National System for Prevention and Response to Disasters, shifting the main responsibility for action to municipal administrations. In Nicaragua, the National System for Disaster Prevention, Mitigation and Response (SINAPRED) works with local government to integrate disaster mitigation and risk reduction into local development

Frequently Asked Questions

FAQ 8.1 | Do experiences with disaster risk reduction in urban areas provide useful lessons for climate-change adaptation?

There is a long experience with urban governments implementing disaster risk reduction that is underpinned by locally driven identification of key hazards, risks, and vulnerabilities to disasters and that identifies what should be done to reduce or remove disaster risk. Its importance is that it encourages local governments to act before a disaster—for instance, for risks from flooding, to reduce exposure and risk as well as being prepared for emergency responses prior to the flood (e.g., temporary evacuation from places at risk of flooding) and rapid response and building back afterwards. In some nations, national governments have set up legislative frameworks to strengthen and support local government capacities for this (Section 8.3.2.2). This is a valuable foundation for assessing and acting on climate-change related hazards, risks, and vulnerabilities, especially those linked to extreme weather. Urban governments with effective capacities for disaster risk reduction (with the needed integration of different sectors) have institutional and financial capacities that are important for adaption. But while disaster risk reduction is informed by careful analyses of existing hazards and past disasters (including return periods), climate change adaptation needs to take account of how hazards, risks, and vulnerabilities will or might change over time. Disaster risk reduction also covers disasters resulting from hazards not linked to climate or to climate change such as earthquakes.

processes (von Hesse et al., 2008; IFRC, 2010). Other initiatives in Central and South America include the influence of La Red (IFRC, 2010), the DIPECHO project "Developing Resilient Cities," and UNDP and GOAL in Central America. In growing numbers of cities in Asia (Shaw and Sharma, 2011) and Africa (Pelling and Wisner, 2009), experiences with community-driven "slum" or informal settlement upgrading has led to a recognition of its potential to reduce risk and vulnerability to extreme weather events, most effectively when supported by local government and civil defense response agencies (Boonyabancha, 2005; Archer and Boonyabancha, 2011; Carcellar et al., 2011).

The Homeless People's Federation of the Philippines developed a series of effective responses following major disasters, including community-rooted data gathering (assessing destruction and victims' immediate needs); trust and contact building; support for savings; registering community organizations; and identifying needs, including building materials loans for repairs. The effectiveness of these measures is much enhanced with local government support (Carcellar et al., 2011) and these experiences have helped inform community-based adaptation (Section 8.4).

International networks supporting innovation in disaster risk reduction and/or climate change adaptation and inter-city learning include La Red in Latin America which has been operating for 3 decades (IFRC, 2010) and the cities program of the Asian Disaster Preparedness Centre (ADPC). As donor interest has grown in supporting disaster risk management as a vehicle for climate change adaptation, a number of urban resilience programs have developed including ACCCRN (Asian Cities Climate Change Resilience Network; Brown et al., 2012), the UNISDR (United Nations International Strategy for Disaster Reduction Making Cities Resilient) network (Johnson and Blackburn, 2013), the ICLEI (Local Governments for Sustainability) city adaptation network, and UN-HABITAT's Cities and Climate Change Initiative.

Despite growing international support for urban disaster risk management, local governments have difficulty accessing the resources to make real change (von Hesse et al., 2008). Local government risk reduction investments are not seen as priorities and have to compete for scarce resources with what are judged to be more pressing needs. Effective policies are often tied to the terms of particular mayors or political parties (Mansilla et al., 2008; Hardoy et al., 2011). In most cases, risk reduction is not integrated into development plans or all relevant local government departments. Manizales, Colombia, is an exception: risk reduction has long been seen as part of local development and collective interests take precedence over party political interests (Hardoy and Velasquez Barrero, 2013).

Disaster risk management is increasingly positioned as a frontline sector for integrating climate change adaptation into everyday decision making and practices (IPCC, 2012), as seen in the plans of municipalities such as Tegucigalpa and Montevideo (Aragón-Durand, 2011). Where it is taken seriously, it offers real opportunities for synergy as the long-range nature of climate change concerns and its policy visibility can enhance local support for disaster risk management. There is considerable scope in international frameworks and national responsibilities for better coordination to make urban disaster risk management climate resilient (Aragón-Durand, 2008; IPCC, 2012).

8.3.3. Adapting Key Sectors

8.3.3.1. Adapting the Economic Base of Urban Centers

Section 8.2 described how climate change can change the comparative advantages of cities and regions—for instance, by influencing climate sensitive resources, water availability, and flooding risks. Many case studies show how extreme weather can impede economic activities, damaging industrial infrastructure and disrupting ports and supply chains (Section 8.2.3.4). Vugrin and Turnquist (2012) discuss design for resilience in distribution networks such as electric power, gas, water, food production, and manufacturing supply chains. This requires absorptive capacity (to withstand extreme weather), adaptive capacity (e.g., service provision through alternative paths), and restorative capacity (quick and cheap recovery).

When urban centers fail to adapt to risks, it may discourage new investment and lead enterprises to move or expand to safer locations. Multinational corporations and many national businesses are adept at changing location in response to changing opportunities and risks, including high insurance costs. Disasters can change perceptions of risk. Businesses may adapt to avoid impacts in their own facilities but be affected by impacts to utilities and other businesses or to their workforce and the services they use (schools, hospitals) (Hallegatte et al., 2011a; da Silva, 2012). Limited local capacity to reconstruct means increased vulnerability to future extreme events and less new investment weakens the economic base (Benson and Clay, 2004; Hallegatte et al., 2007b, 2011a). Past experience in the USA and Europe show the difficulties city governments can face in attracting new investment when a city or region's main activity weakens. If climate change forces changes to economic structure and business models, transitions may be hard to manage (Berger, 2003). Specific adaptation policies may make the transition more rapid and less painful. For instance, adaptation is generally cheaper and easier in greenfield sites—as low-risk sites are chosen, trunk infrastructure to appropriate standards is installed and building and land use regulations enforced. Retrofitting existing infrastructure and industries is generally more expensive (McGranahan et al., 2007).

Within and around urban centers, local governments may require several strategies to strengthen resilience including selective relocation, better land use planning, and revised building regulations to retrofit or flood-proof structures (Hanson et al., 2011). Synergies can be encouraged where land use management around a city supports rural livelihoods, and protects ecosystem services (Section 8.3.3.7). There may be opportunities for proactive adaptation outside larger cities where much of the future urban growth will occur. Manizales, Colombia, which has long had innovative environmental and disaster risk reduction policies has begun incorporating climate change and environmental management into its local development agenda, including the establishment of city climate monitoring systems (Hardoy and Velasquez Barrero, 2013). But most smaller urban centers are institutionally weaker and may lack the investment capacity and critical infrastructure.

Adapting the urban economic base may require short- and long-term strategies to assist vulnerable sectors and households. The consequences of climate change for urban livelihoods may be particularly profound

Frequently Asked Questions

FAQ 8.2 | As cities develop economically, do they become better adapted to climate change?

Cities and nations with successful economies can mobilize more resources for climate change adaptation. But adaptation also needs specific policies to ensure provision for good quality risk-reducing infrastructure and services that reach all of the city's population and the institutional and financial capacity to provide, and manage these and expand them when needed. Poverty reduction can also support adaptation by increasing individual, household, and community resilience to stresses and shocks for low-income groups and enhancing their capacities to adapt. This provides a foundation for building climate change resilience but additional knowledge, resources, capacity, and skills are generally required, especially to build resilience to changes beyond the ranges of what have been experienced in the past.

for low-income households who generally lack assets or insurance to help them cope with shocks (Moser and Satterthwaite, 2009). The informal sector is a significant part of the economy for most urban centers, providing employment for large numbers. But the effects of extreme weather on the informal economy are rarely considered, as in 2003 floods in Santa Fe, Argentina (Hardoy and Pandiella, 2009). In Kelurahan Pabean Pekalongan in Central Java, batik production, the primary livelihood, is being disrupted by increasingly frequent floods (UN-HABITAT, 2011b). Cash transfers and safety nets are being considered to help low-income groups cope with the short-term impacts of climate change (Sanchez and Poschen, 2009), as well as climate variability. But these will not address all the risks they face or support collective or public investments in risk-reducing infrastructure and services.

There is a growing discussion of the importance of support for a "green economy" with green infrastructure to help shift nations' economic and employment base toward lower carbon, more resilient, more sustainable patterns that respect regional and global ecological and resource limits. For urban centers, this means highlighting new (or adapted) business opportunities that limit anthropogenic climate change, resource depletion, and environmental degradation. Sometimes social inclusivity and eco-efficiency are included as mutually reinforcing principles (e.g., Allen and Clouth, 2012). The literature has begun to explore the changes needed in production systems (especially in carbon intensity, waste generation, and management), buildings, transport systems, electricity generation (including incorporating solar and wind), and consumption patterns of wealthier groups (Hammer et al., 2011; UN-HABITAT, 2012a,b,c,d; World Economic Forum, 2013). As yet, there is too little detailed discussion of how a green economy can be fostered in relation to particular cities or in regard to the incentives and regulations that can shift private investment to this.

The 'waste economy' in cities in low- and middle-income nations is important to the green economy, providing livelihoods (Hardoy et al., 2001; Hasan et al., 2002; Medina, 2007) and contributing to waste reduction and GHG emission reduction (Ayers and Huq, 2009). In Brazil's main cities, more than half a million people are engaged in waste picking and recycling (Fergutz et al., 2011), in Lima an estimated 17,000, and in Cairo 40,000 (Scheinberg et al., 2011). The ways city governments choose to work with (or ignore) those in this waste economy have obvious implications for employment and for resource use.

For some cities, there is documentation of the adaptation costs to protect or enhance the economic base. Hallegatte et al. (2013) assess present and future flood losses in the world's 136 largest coastal cities and show that the estimated costs of adaptation are far below the estimate of losses in the absence of adaptation. The paper also highlights the differences in the cities most at risk, depending on whether the ranking is by economic average annual losses or by such losses as a proportion of each city's GDP. In the first, it is mainly cities in high-income nations, in the second, mainly prosperous cities in middle-income nations.

Mombasa may have to redesign and reconstruct the city's ports, protect cement industries and oil refineries, and relocate some industries inland, all requiring major capital investments (Awuor et al., 2008). Adaptation can help protect many parts of Rio de Janeiro's diverse economy (including manufacturing, oil refineries, shipyards, and tourism) and the large populations living in informal settlements (favelas) on land at risk of landslides (de Sherbinin et al., 2007). Defenses needed to safeguard coastal industries and residential areas could threaten Rio's beach tourist industry and cause further erosion to other unprotected areas. As in most cities, making Rio's economic base more resilient to climate change means resolving such trade-offs and encouraging dialog among local stakeholders (Ruth, 2010).

As yet, there is little evidence that cities' adaptive capacities influence private sector investments. But private investment is influenced by the quality and availability of infrastructure and services that are an essential part of adaptive capacity. Many cities in Asian high growth economies are located in low-elevation coastal zones undergoing rapid urbanization and economic transformation (McGranahan et al., 2007). Cyclones are common in many of these coastal settlements. Rising concentrations of people, infrastructure, and industries along India's coasts, without adaptation, could mean nonlinear increase in vulnerability over the next 2 decades (Revi, 2008). The same is true for China (McGranahan et al., 2007). In most nations, urban governments find it difficult to prevent new developments on sites at risk of flooding, especially in locations attractive for housing or commerce, even when there are laws and regulations in place to prevent this (see Olcina Cantos et al., 2010, for an example in Alicante in Spain).

There are few economic assessments of climate change risks in West African coastal cities. Many cities or districts and their industries,

Frequently Asked Questions

FAQ 8.3 | Does climate change cause urban problems by driving migration from rural to urban areas?

The movement of rural dwellers to live and work in urban areas is mostly in response to the concentration of new investments and employment opportunities in urban areas. All high-income nations are predominantly urban and increasing urbanization levels are strongly associated with economic growth. Economic success brings an increasing proportion of GDP and of the workforce in industry and services, most of which are in urban areas. While rapid population growth in any urban center provides major challenges for its local government, the need here is to develop the capacity of local governments to manage this with climate change adaptation in mind. Rural development and adaptation that protects rural dwellers and their livelihoods and resources has high importance as stressed in particular in Chapters 9 and 13—but this will not necessarily slow migration flows to urban areas, although it will help limit rural disasters and those who move to urban areas in response to these.

infrastructure and tourism will be a challenge to protect, as in Cotonou (Dossou and Gléhouenou-Dossou, 2007), Lagos (Douglas et al., 2008), and Dakar (Wang et al., 2009).These and other important economic centers in the Gulf of Guinea (including Abidjan and Port Harcourt) have large areas close to mean sea level and highly vulnerable to erosion and rising sea levels. Rapid construction, destruction of mangrove swamps, and inadequate refuse collection compound the risks (Simon, 2010).

8.3.3.2. Adapting Food and Biomass for Urban Populations

Many urban dwellers in low- and middle-income countries suffer hunger, while a larger number face food and nutrition insecurity (Montgomery et al., 2003; Ahmed et al., 2007; Cohen and Garrett, 2010; Crush et al., 2012) owing more to their low incomes than to overall food shortages (Cohen and Garrett, 2010; Crush et al., 2012). For these low-income urban households, food expenditures generally represent more than half of total expenditures (Cohen and Garrett, 2010), putting them at particular risk from real increases in long-term food prices or temporary spikes associated with disasters.

Climate change impacts can have far-reaching influences on food security and safety, but these "will crucially depend on the future policy environment for the poor" (Schmidhuber and Tubiello, 2007, p. 708; see also Douglas, 2009). Agriculture has managed to keep up with rising demands worldwide, despite rapid population growth, the reduction in agricultural workers that accompanies urbanization, and dietary shifts that are more carbon and often land intensive (Satterthwaite et al., 2010). But food security may be eroded by competing pressures for water or bio-fuels. In addition, there may be tensions between managing land use to reduce flood risk and food and energy policies (Wilby and Keenan, 2012). Adapting urban food systems represents a major challenge and will necessitate radical changes in food production, storage, and processing (and in reducing waste), in transport/the supply chain, and in access (Godfray et al., 2010). Both supply and demand side constraints must be considered. Climate change-related constraints on agricultural production affect urban consumers through reduced supplies or higher prices; falling production and farmer incomes reduces their demand for urban goods and services; disruption to urban centers can mean disruption to the markets, services, or remittance flows on which agricultural producers rely (Tacoli, 2003). Thus, strengthening urban food security needs to take account of complex rural-urban linkages (Revi, 2008) and responses must bridge rural and urban boundaries.

Urban centers that are seriously impacted by extreme weather face serious challenges in ensuring that those affected have access to adequate and safe food and water supplies. Flooding, drought, or other extreme events often lead to food price shocks in cities (Bartlett, 2008) as well as spoiling or destroying food supplies for many households. After the 2004 floods in Bangladesh, Dhaka's rice prices increased by 30% and vegetable prices more than doubled, with urban slum dwellers and rural landless poor the worst affected (Douglas, 2009). When facing increased food prices, the urban poor adopt a range of strategies such as reduced consumption, fewer meals, purchasing less nutritious foods, or increasing income earning work hours, particularly for women and children (Cohen and Garrett, 2010). But these erode nutrition and health status, especially of the most vulnerable and fail to strengthen resilience, particularly in the context of more frequent disasters.

Adaptive local responses include support for urban and peri-urban agriculture, green roofs, local markets, and enhanced safety nets. Food price increases may be moderated by improving the efficiency of urban markets, promoting farmers' markets, and investing in infrastructure and production technologies (Cohen and Garrett, 2010). Food security may be enhanced by support for urban agriculture and street food vendors (Cohen and Garrett, 2010; Lee-Smith, 2010) and access to cheaper food or measures such as cash transfers (e.g., Brazil's Bolsa Familia Programme) or, for older groups, pensions (Soares et al., 2010). Initially rural in focus, cash transfer programs have expanded in urban areas, in some places reaching much of the low-income population (Johannsen et al., 2009; Niño-Zarazúa, 2010; Mitlin and Satterthwaite, 2013).

8.3.3.3. Adapting Housing and Urban Settlements

The built environment in urban areas has to adapt to the range of climate change impacts outlined in Section 8.2, in order to protect urban populations and economies and protect among society's most valuable

assets. Knowledge and innovation are required for adapting existing and new buildings. This will be built on the bedrock of affordable housing appropriate for health and safety, built to climate-resilient standards and with the structural integrity to protect its occupants long term against extreme weather (UNISDR, 2009, 2011). The resilience of poor quality housing, often at risk from extreme weather, can be enhanced via structural retrofitting, interventions that reduce risks (for instance, expanding drainage capacity to limit or remove flood risks), and non-structural interventions (including insurance). Attention to all three is more urgent where housing quality is low, where settlements are on high-risk sites, and in cities where climate change impacts are greatest. Enhancing the resilience of buildings that house low-income groups will usually be expensive and may face political challenges (Roaf et al., 2009).The range of actors in the housing sector, the myriad connections to other sectors and the need to promote mitigation and adaptation, as well as development goals, point to the importance of well-coordinated strategies that can support resilience (Maller and Strengers, 2011).

There have been studies in increasing numbers of cities to identify measures to adapt housing (and other buildings) and discussions on revising standards, although it is difficult to set standards with uncertain forecasts and scenarios and evolving risks (Engineers Canada, 2008). There is less evidence of the action plans, budget commitments, and regulation changes to implement them. Measures identified in a Bangkok assessment included flood-proofing homes, building elevated basements, and moving power-supply boxes upstairs, along with keeping enough food, water, fuel, and other supplies for 72 hours; it also pointed to regulatory changes to bolster resilience including land use restrictions in floodplains and other at-risk sites and revised safety and fire codes for buildings and other structures (BMA, GLF, and UNEP, 2009). Cape Town's climate change framework (2006) proposed housing interventions including regulations for building informal housing, in part to reduce the need for emergency response and anticipate projected climate change. Regulations in New York and Boston are being updated to address climate-related risks (City of Boston, 2011; City of New York, 2011). London and Melbourne's adaptation plans both consider strategies combining green infrastructure and housing interventions (GLA, 2010; UN-HABITAT, 2011a).

8.3.3.3.1. Housing and other buildings and extreme heat

More attention is being paid to extreme heat in particular cities (e.g., City of Chicago 2008, 2010; City of Toronto, 2013; Tomlinson et al.,2011, for Birmingham; Matzarakis and Endler, 2010, for Freiberg; GLA, 2010, for London; and Giguère, 2009, for Quebec), also in regard to low-income housing in Athens (see Sakka et al., 2012).

Attention is required to buildings that provide protection from hot days and to populations more vulnerable to extreme heat, including those who work outside (see Box CC-HS). In locations with large daily variations in temperature, the response can include upgrading homes with limited ventilation and low thermal mass. Chicago's 2008 Climate Action Plan discussed the need for innovative cooling ideas for property owners (City of Chicago, 2008, p. 52). Air conditioning and other forms of mechanical cooling are too expensive, unavailable for the many urban households with no electricity, and maladaptive when electricity generation contributes to GHG emissions. Residents' vulnerabilities may be exacerbated if electricity supplies are unreliable; blackouts tend to occur on the hottest days when demand is highest (Maller and Strengers, 2011, p. 3). The literature on adaptations for extreme heat focuses on high-income nations and more attention is required to this in urban centers in low- and middle-income nations.

Passive cooling can be used in both new-build and retrofitted structures to reduce solar and internal heat gains, while enhancing natural ventilation or improving insulation (Hacker and Holmes, 2007; Roberts, 2008a,b). Passive designs, using super-insulation, ventilation, and other measures to ensure energy is not required for most of the year, as in the Beddington Zero Energy Development (BedZED) in London (Chance, 2009) or Germany's Passive Haus standard (Rees, 2009), have set precedents for mitigating household emissions but they can simultaneously contribute to adaptation. Thermal mass can be used for cooling, "because it introduces a time-delay between changes in the outside temperature and the building's thermal response necessary to deal with the high daytime temperatures" (Hacker and Holmes, 2007, p. 103). Structures in southern Europe already use solar shading, ventilation, and thermal mass to promote enhanced cooling (Hacker and Holmes, 2007). Simulations for London (under UKCIP02 Medium-High emissions scenarios) suggest that passive designs are an "eminently viable option for the UK, at least over the next 50 years or so" (Hacker and Holmes, 2007, p. 111). There are several obstacles though: opening windows may be hampered by security concerns or noise pollution (Hacker and Holmes, 2007). Modern windows may not ventilate well, and site restrictions and cost can impede the use of passive cooling in refurbishing existing buildings (Roberts, 2008a).

8.3.3.3.2. Housing and disaster-preparedness measures

When populations are displaced or temporarily evacuated, provision for emergency shelters and services have to be able to respond, especially for vulnerable residents. For instance, after Cyclone Larry in Queensland (in 2006) and New South Wales' coastal flooding (in 2007), officials recalled the strains faced in shelters and the coordination difficulties with emergency health workers, police, insurance, and other agencies (Jacobs and Williams, 2011). This points to the range of social support, structural strategies, and interagency efforts that local authorities may develop to adapt to climate change. For many urban centers, there is also the issue of how to move populations at risk, which presents many challenges (Roaf et al., 2009).

Urban centers facing extreme heat require plans that provide early warning for citizens, inform them of measures they can take and ensure adequate water provision, back up electricity, emergency health care, and other public services focused on vulnerable residents, especially infants and the elderly in hospitals and residential facilities (Brown and Walker, 2008; Hajat et al., 2010) or living alone. Public buildings with cooling may also be required. Cities with responses to hot days for those most at risk are mainly from high-income nations. Several hundred million urban dwellers in low- and middle-income nations have no access to electricity (Johansson et al., 2012) or mechanical devices that help with cooling.

8.3.3.4. Adapting Urban Water, Storm, and Waste Systems

It is challenging to summarize key adaptation strategies from the highly heterogeneous mix of urban areas across the globe. In high-income and some middle-income nations, virtually all the urban population is served by drinking quality water piped to the home 24 hours a day, by systems of sanitation that minimize risks of fecal contamination and by storm and surface drainage. Many urban centers in such nations may face serious climate change-related challenges for water, but do not have to address the fact that much of their population lacks piped water, toilets, or storm drains. They can also bill users for much of the funds required for water provision and management.

At the other extreme are a very large number of urban centers with large deficits in provision for water, sanitation, and drainage and with weak, under-resourced institutions (UN-HABITAT, 2003b; UNEP, 2012). Around a billion people live in informal settlements where providers responsible for water and sanitation are often unwilling to invest or not allowed to do so (Mitlin and Satterthwaite, 2013). New York City can develop a plan to ensure adequate water supplies costing billions of dollars (Solecki, 2012); many cities in sub-Saharan Africa have not only very large deficits in piped water, sewers, and drains but also very limited investment capacities (see, e.g., Kiunsi, 2013, for Dar es Salaam).

Some studies have sought to estimate the costs of adapting urban water and sanitation systems, pointing to the need for significant investments (Arnell, 2009). Muller (2007) suggests that US$1 to 2.7 billion is required annually in sub-Saharan African cities to adapt existing water infrastructure; this does not include the cost of addressing deficient infrastructure. Another US$1 to 2.6 billion a year is required to adapt new developments (including water storage, waste water treatment, and electricity generation).

8.3.3.4.1. Adapting urban water supply systems

For cities with climate change adaptation plans, water and waste water management are usually important components (see, e.g., Helsinki Region Environmental Services Authority, 2012). Major et al. (2011) list a range of cities that have begun to adapt water systems and other infrastructure including Boston, London, Halifax (Canada), New York, Seattle, and Toronto. The U.S. government has developed a guide for adaptation strategies for water utilities (EPA, 2013). But developing such measures is not yet commonplace.

Supply-side approaches to seasonal water shortages are frequently advocated. An analysis of 21 draft Water Resources Management Plans in the UK found that agencies usually favored reservoirs and other supply-side measures to adapt to climate change, although authors suggest that demand-side interventions may also be needed (Charlton and Arnell, 2011). To expand its reservoir capacity after 1998 floods exposed existing infrastructure, Rotterdam developed plans combining adaptation and urban renewal goals, mixing economic activities with water-based adaptive designs, including "water retention squares" and green roofs, floating houses, and networks of channels (Van der Brugge and De Graaf, 2010). Seattle has used demand-side strategies to cut water consumption including aggressive conservation measures, system savings, and price increases (Vano et al., 2010).

In Mexico City, a number of measures in the water sector have been proposed many times since the 1950s but not acted on, including a decrease in water use and the restoration and management of urban and rural micro-basins (Romero-Lankao, 2010). Adaptation measures have been conceived as too general and lacking institutional commitment. In Durban, where the water sector is revenue earning and seen as critical to development, the importance of climate change adaptation was recognized as a priority (Roberts, 2010). In Cape Town, which faces profound challenges in ensuring future supplies, water management studies identified the need to consider climate change and population and economic growth (Mukheibir and Ziervogel, 2007). During the 2005 drought, the local authority substantially increased water tariffs, considered a most effective way to promote efficient water usage (Mukheibir, 2008). Other measures may include water restrictions, reuse of gray water, consumer education, or technological solutions such as low-flow systems or dual flush toilets (Mukheibir and Ziervogel, 2007).

In Phoenix, Arizona, a rapidly expanding desert city projected to reach 11 million people by 2050, most peripheral growth depends on groundwater (Bolin et al., 2010). Simulations explored how water usage may be reduced to achieve safe yield while accommodating future growth. Reducing current high use may be achieved through urban densification, increased water prices, and water conservation measures (Bolin et al., 2010). Gober et al. (2010) agree that stringent demand and supply policies can forestall "even the worst climate conditions and accommodate future population growth, but would require dramatic changes to the Phoenix water supply system" (Gober et al., 2010, p. 370). Here and in other cities in Arizona, supply-side management including active management of groundwater and groundwater storage is combined with extensive demand side measures (Colby and Jacobs, 2007).

In Quito, where reduced freshwater supplies are projected with glacier retreat and other climate-related changes, local government has formulated a range of adaptation plans, including encouraging a culture of rational water use, reducing water losses, and developing mechanisms to reduce water conflicts (Hardoy and Pandiella, 2009). However, community participation in planning and implementation has not been considered (Hardoy and Pandiella, 2009). Participatory water planning has occurred elsewhere in Latin America: stakeholders in Hermosillo, Mexico, identified and prioritized specific adaptations such as rainwater harvesting and water-saving technologies (Eakin et al., 2007).

Several cities actively encourage rainwater harvesting while others are considering its potential. Since 2004, in New South Wales, Australia, homeowners have been required to ensure that newly built houses use 40% less potable water than an established benchmark level of consumption, through water-saving measures such as water-efficient shower heads, dual-flush toilets, rainwater tanks and grey water treatment systems (Warner, 2009). Many low-income Caribbean households rely on rainwater collection systems for domestic use. Extending existing communal collection and distribution systems would require community financing or governmental interventions, as well as overcoming resistance from higher-income residents (Cashman et al., 2010). Rainwater harvesting has been promoted in several cities in India (Shaban and Sharma, 2007).

8.3.3.4.2. Waste and storm water management

More attention has been given to adaptations to help ensure sufficient water supplies than to increasing the capacity of sewer and drainage systems, or adapting them to allow for the impacts of heavier rainfall or sea level rise. We noted earlier the very large deficiencies in provision for drainage for urban centers in low- and many middle-income nations.

In St. Maarten, Netherlands Antilles, the government (after a storm water modeling study) is developing a flood warning system and considering such institutional adaptations as a new decision-support framework, centralized geographic information system (GIS) for infrastructure planning and public education, along with structural measures such as draining areas with a high groundwater table (Vojinovic and Van Teeffelen, 2007). City management in Toronto, Canada, has prioritized an upgrade of storm water and wastewater systems (Kessler, 2011). Deak and Bucht (2011) analyze past hydrological structures in Lund, Sweden, and use the concept of indigenous blue infrastructure to question current storm water management in the urban core. Cities in California have a range of flood management methods but Hanak and Lund (2012) suggest that they will also require forward-looking reservoir operation planning and floodplain mapping, less restrictive rules for raising local funds, and improved public information on flood risks. Willems and Arnbjerg-Nielsen (2013) suggest that climate change adaptation for urban drainage systems requires a reevaluation of the technical solutions implemented over the last 150 years. The objective is cities that interact with water (including storms) in a healthy, environmentally friendly, and cost-efficient way. This includes the incorporation of roads and parks into the active drainage system and the use of blue and green storm water infrastructure (Section 3.3.3.7). These authors also note that this implies changing roles for water scientists, water managers, and water engineers as well as for water users, property owners, insurers, city planners, and politicians (Willems and Arnbjerg-Nielsen, 2013; see also Willems et al., 2012). Many governments in the last 20 years have developed integrated water resource management (UNEP, 2012) with linkages between provisions for water, sanitation, and drainage and other sectors, and a recognition of the need to work with a range of partners, consider broader development goals, identify tensions or trade-offs (Willems and Arnbjerg-Nielsen, 2013), and implement low-regret anticipatory solutions. For cities, this often includes management of groundwater use and water catchment in areas outside their jurisdiction and thus collaboration with other local governments (WMO, 2008). Most examples of this are in high-income nations (for an exception, see Bhat et al., 2013).

Urban water systems usually depend on reliable electricity supplies and can be energy intensive—for instance, in conveying or treating water from distant or low-quality sources. Integrated planning (e.g., in concert with energy conservation, water catchment management and green infrastructure strategies) can minimize conflicts, support local industries, and ensure equitable access to water in cities.

8.3.3.5. Adapting Electric Power and Energy Systems

The heavy dependence of urban economies, infrastructure, services, and residents on electricity and fossil fuels means far-reaching consequences if supplies are disrupted or unreliable (Section 8.2.4.2). With mitigation concerns dominating the literature and urban energy policy discussions, there is less focus on adaptation issues (Carmin et al., 2009; Mdluli and Vogel, 2010). The UNFCCC's estimates for investment to address climate change (UNFCCC, 2007) did not include the costs of adapting the energy sector (Fankhauser, 2010). Key issues relating to energy sector adaptation, including generation and distribution, are usually national or regional and are discussed in Chapter 10. But urban governments' and residents' responses are also important. Research has suggested that "private autonomous measures will dominate the adaptation response as people adjust their buildings, [or] change space-cooling and -heating preferences..." (Hammer et al., 2011, p. 27). A few cities have adaptation initiatives underway for energy systems; others have begun to consider the steps needed (Hammer et al., 2011). Some relevant local urban concerns are the extent of the need for autonomous provision or back-up generating capacity, and the functioning of emergency services when energy supplies are disrupted or unreliable. The interrelations between energy and other sectors suggest the need for an integrated approach in understanding vulnerability and shaping appropriate responses (Gasper et al., 2011).

Despite growing concern about the potential impact of climate change and extreme weather events for the oil industry in Canada, USA, and Mexico and how hurricanes, floods, and sea level rise will disrupt oil, gas, and petrochemical installations (Levina et al., 2007; Savonis et al., 2008), few adaptation studies have been undertaken.

8.3.3.6. Adapting Transport and Telecommunications Systems

Urban centers depend on transport and telecommunications systems for daily functioning and for vital regional, national, and international supply chains. For instance, 80% of the food consumed in London is imported (Best Foot Forward, 2002). The Great Lakes–St. Lawrence route in the USA supports 60,000 jobs and US$3 billion worth of annual movement of goods (Ruth, 2010). Most large and successful cities have also spread spatially, and well-functioning transport systems support the decentralization of the workforce and businesses. Many cities, for instance, depend on underground electric rail systems which require protection from the considerable risk from flooding, such as New York and London (Eichhorst, 2009). Adapting all these systems to the impacts of climate change (including hot days, storms, and sea level rise) poses many challenges (Mehrotra et al., 2011b).

8.3.3.6.1. Transport systems

Four different aspects to adaptation strategies for transport can be highlighted: maintain and manage; strengthen and protect; enhance redundancy; and, where needed, relocation. Cities that have developed adaptation plans usually include attention to more resilient transport systems (UN-HABITAT, 2011a). Melbourne's adaptation plan notes that intense storms and wind may lead to blocked roads and disrupt traffic lights, trains, and trams and that these disruptions can be exacerbated by such compounding factors as power disruptions and emergency situations (City of Melbourne, 2009). Adaptation will require transport planners to take a whole-of-life approach to managing infrastructure,

and constantly update risk assessments (Love et al., 2010). Coordination at national, regional, and local levels is important for implementing adaptation strategies in the transport sector, as climate change impacts are widespread and extend across scales (Regmi and Hanaoka, 2011). Interdisciplinary approaches can include changing meteorological hazards as well as social and political values and the governance framework for more resilient transport systems (Jaroszweski et al., 2010).

8.3.3.6.2. Adapting roads

Climate change may increase the costs of maintaining and repairing road transport networks (see Hayhoe et al., 2010, for discussion of changing conditions in Chicago). In Durban, revised road construction standards may be needed (Roberts, 2008). Coastal road adaptation may require strengthening barriers and designing roads or realigning them to higher locations to cope with sea level rise (Regmi and Hanaoka, 2011).

Transport planners are beginning to reassess maintenance costs and traditional materials—for instance, stiffer binding materials to cope with rising temperatures and softer bitumen for colder regions (Regmi and Hanaoka, 2011). But cost considerations may impede their use. The Chicago Department of Transportation decided not to use more permeable, adaptive road materials because of higher cost, although costs may fall with greater economies of scale as demand rises for such materials (Hayhoe et al., 2010). Road maintenance costs vary widely, depending on local context, and future climate scenarios. In Hamilton, New Zealand, increases in rainfall in spring (within one scenario) or winter (in another) would increase road repair costs while decreases in rainfall in other seasons could decrease them; results depend upon the scenario and further investigation was recommended (Jollands et al., 2007).

8.3.3.6.3. Adapting surface and underground railways

Underground transport systems are specific to cities and of great importance to the functioning of many major cities. They may have "particular vulnerabilities related to extreme events, with uniquely fashioned adaptation responses" (Hunt and Watkiss, 2011, p. 14). Heat impacts are often significant, as these systems gradually warm due to engine heat, braking systems, and increased passenger loads. To cope with increasing frequency of hot days, substantial investments in ventilation or cooling may be necessary (Love et al., 2010). For New York City's subways, the system's age, fragmented ownership, overcapacity, and in some cases floodplain location may augment the challenge of adaptation (Zimmerman and Faris, 2010, pp. 69-70). Storm surge flooding from Hurricane Sandy flooded eight under-river subway tunnels, severely impacting mobility and economic activity (Blake et al., 2012).

Rail systems that struggle to cope with existing climate variability may require considerable investment to withstand higher temperatures and more extreme events (see Baker et al., 2010). Railway systems may be more vulnerable to climate variability than the road system, which can more easily redirect traffic (Lindgren et al., 2009). The costs of delays and lost trips due to extreme weather events, analyzed in Boston (Kirshen et al., 2008) and Portland (Chang et al., 2010) were found to be small relative to the damage to infrastructure and other property. Floodplain restoration, use of porous pavements, and detention ponds may help address the projected increased flooding in Portland (Chang et al., 2010).

In flood-prone cities, transport systems may require more stringent construction standards, design parameters, or relocation. Much of central Mumbai is built on landfill areas and prone to flooding, but they contain the main train stations and train lines as well as large populations and a large part of the city's economy. Rising sea levels may cause shifts at the sub-surface level of landfill areas and structural instabilities (de Sherbinin et al., 2007).

8.3.3.6.4. Ports

Section 8.2 outlined the many ways in which ports can be impacted by climate change and the investments required to take account of these. Many ports remain largely unaware of the potential threats of climate change, or are slow to consider appropriate adaptation measures (Becker et al., 2012). Rotterdam's Climate Proof Programme includes as key components flood safety and accessibility for ships and passengers (Rotterdam Climate Initiative, 2010; Vellinga and De Jong, 2012). A climate risk study for the Port of Muelles el Bosque (Cartagena, Colombia) analyzed projected changes in sea level rise, storm surge height, precipitation, temperature, and wind patterns and their direct and indirect effects on port assets and operations, surrounding environment and communities, and on the trade of goods transported through the port and this helped catalyze adaptation investments (Stenek et al., 2011).

There are also the deficits in basic infrastructure noted in Section 8.2 that inhibit adaptation including the lack of all-weather roads and paths in informal settlements that constrain rapid evacuation and limit access for emergency vehicles.

8.3.3.6.5. Telecommunications

A wide range of components and sub-systems for telecommunications systems that are within cities may need adaptation to the impacts of climate change, including telephone poles and exchanges, cables, mobile telephone masts and data centers (Engineering the Future, 2011; Chapman et al., 2013).

8.3.3.7. Green Infrastructure and Ecosystem Services within Urban Adaptation

Ecosystem based adaptation has relevance for many chapters (see Box CC-EA). Ecosystem-based adaptation in urban areas as part of the climate change adaptation strategy seeks to move beyond a focus on street trees and parks to a more detailed understanding of the ecology of indigenous ecosystems, and how biodiversity and ecosystem services can reduce the vulnerability of ecosystems and people. Strategies to achieve biodiversity goals (developing corridors for species migration, enlarging core conservation areas, identifying areas for improved matrix

Box 8-2 | Ecosystem-Based Adaptation in Durban

Durban has adopted an ecosystem-based adaptation approach as part of its climate adaptation strategy. This required a series of steps (Roberts et al., 2012):

- A better understanding of the impacts of climate change on local biodiversity and the management Durban's open space. The projected warmer and wetter conditions seem to favor invasive and woody plant species.
- Improved local research capacity that includes generating relevant local data.
- Reducing the vulnerability of indigenous ecosystems as a short-term precautionary measure.
- Enhancing protected areas owned by local government and developing land use management interventions and agreements to protect privately owned land areas critical to biodiversity and ecosystem services. This can be supported by government incentives and regulation to stop development on environmentally sensitive properties, the removal of perverse incentives, and support for affected landowners.
- The promotion of local initiatives that contribute jobs and promote skills and environmental education within ecosystem management and restoration programs. Durban has initiated a large-scale Community Reforestation Programme where community level "tree-preneurs" produce indigenous seedlings and help plant and manage the restored forest areas as part of a larger strategy to enhance biodiversity refuges and water quality, river flow regulation, flood mitigation, sediment control, and improved visual amenity. Advantages include employment creation, improved food security, and educational opportunities.

management to enhance ecological viability) can have adaptation co-benefits. Recognizing that the adaptation deficit is both in the lack of conventional infrastructure and the loss of ecological infrastructure, the approach includes an interest in how ecosystem restoration and conservation can contribute to food security, urban development, water purification, waste water treatment, climate change adaptation, and mitigation (Roberts et al., 2012). The growing attention to ecosystem services includes adaptations in urban, peri-urban, and rural areas that use opportunities for the management, conservation, and restoration of ecosystems to provide services and increase resilience to climate extremes. They can also deliver co-benefits (e.g., purifying water, absorbing runoff for flood control, cleansing air, moderating temperature, and preventing coastal erosion) while helping contribute to food security and carbon sequestration (Newman, 2010; Foster et al., 2011b; GLA, 2011; Roberts et al., 2012; see also Institute for Sustainable Communities, 2010; City of New York, 2011; Oliveira et al., 2011; Tallis et al., 2011; Wilson et al., 2011; Helsinki Region Environmental Services Authority, 2012). These approaches are particularly important in low- and many middle-income countries where livelihoods for some urban residents and much of the peri-urban population depend on natural resources. But there are considerable knowledge gaps in determining the limits or thresholds to adaptation of various ecosystems and where and how ecosystem-based adaptation is best integrated with other adaptation measures. There is also some indication that the costs of ecosystem-based adaptation in urban contexts might be higher than expected, in large part because costs are higher for land acquisition and ecosystem management (Roberts et al., 2012; Cartwright et al., 2013).

Box 8-2 describes how ecosystem-based adaptation is being developed in Durban. Another example is addressing flood risk through catchment management that includes community-based partnerships supported by full cost accounting and payment for ecosystem services—rather than the more conventional canalization of rivers (Kithiia and Lyth, 2011; Roberts et al., 2012).

Although much of the early innovation in ecosystem services and green infrastructure was geared to address water shortages or flooding, its importance for climate change adaptation is increasingly recognized.

Green spaces in cities are beneficial for absorbing rainfall and moderating high temperatures. Urban forests and trees can provide shading, evaporative cooling and rainwater interception, and storage and infiltration services for cities (Pramova et al., 2012). Increasing tree cover is proposed as a way to reduce UHI. Cooling effects are especially high in large parks or areas of woodland but the land these are on face competition from developers, as well as management challenges (Pramova et al., 2012). The rapid and often unregulated expansion of cities in low- and middle-income nations may also have left a much lower proportion of the urbanized area as parks and other green spaces.

There is also lack of detailed knowledge on the climatic effects of specific urban plants and vegetation structures (Mathey et al., 2011) and on other important aspects such as the influence of green areas in local circulation patterns and impact on urban fluxes and urban metabolism (Chrysoulakis et al., 2013). In addition, green infrastructure projects may select plant material for particular purposes that do not support habitat values or large ecosystem function and greater ecosystem services.

Some city governments have focused on green infrastructure within built up areas. In the USA, Portland and Philadelphia have encouraged green roofs, porous pavements, and disconnection of downspouts to reduce storm water at much lower cost than increasing storm water storage capacity (Foster et al., 2011b). Some cities have invested in green infrastructure linked to both regeneration and climate change

adaptation. The Green Grid for East London seeks to create "a network of interlinked, multi-purpose open spaces" to support the wider regeneration of the sub-region, enhancing the potential of existing and new green spaces to connect people and places, absorb and store water, cool the vicinity, and provide a mosaic of habitats for wildlife (GLA, 2008, p. 80). New York has a well-established program to protect and enhance its water supply through watershed protection. This includes city ownership of crucial land outside the city and working with land owners and communities to balance protection of drinking water with facilitating local economic development and improving waste water treatment. There is also an ambitious green infrastructure plan within the city, including porous pavements and streets, green and blue roofs, and other measures to control storm water. The program is costly, compared to constructing and operating a filtration plant, but is the most cost-effective choice for New York (Bloomberg and Holloway, 2010; Foster et al., 2011b).

The coastal city of Quy Nhon in Vietnam is reducing flood risks by restoring a 150-hectare zone of mangroves (Brown et al., 2012). Singapore has used several anticipatory plans and projects to enhance green infrastructure including its Streetscape Greenery Master Plan, constructed wetlands or drains, and community gardens (Newman, 2010). Authorities in England and the Netherlands are recognizing the linkages between spatial planning and biodiversity, but without much direct response to climate change adaptation. Barriers to action include short-term planning horizons, uncertainty of climate change impacts, and problems of creating habitats due to inadequate resources, ecological challenges, or limited authority, and data (Wilson and Piper, 2008).

In Mombasa, the Bamburi Cement Company rehabilitated 220 hectares of quarry land (Kithiia and Lyth, 2011). The resulting Haller Park attracts more than 150,000 visitors per year, and has the potential to create adaptation co-benefits. Cape Town has initiated community partnerships to conserve biodiversity, including the Cape Flats Nature project with the para-statal South African National Biodiversity Institute. Participating schools and organizations explore ecosystem services (such as flood mitigation and wetland restoration), and the project facilitates "champion forums" to support conservation efforts (Ernstson et al., 2010, p. 539).

Dedicated green areas within urban environments compete for space with other city-based needs and developer priorities. The role of strategic urban planning in mediating among competing demands is potentially useful for the governance of adaptation as demonstrated in London, Toronto, and Rotterdam (Mees and Driessen, 2011). The experience in Durban (see Box 8-2) also faces many challenges (Roberts et al., 2012), including an assumption that ecosystem-based adaptation is an easy alternative to the constraints that limit the implementation and effectiveness of "hard engineering" solutions (Roberts et al., 2012; Kithiia and Lyth, 2011). Experience in Durban shows that implementing an ecologically functional and well-managed, diverse network of bio-infrastructure requires data collection, expertise, and resources, and to have direct and immediate co-benefits for local communities and ensure integration across institutional and political boundaries. There are substantial knowledge gaps such as determining where the limits or thresholds lie; many ecosystems have been degraded to the point where their capacity to provide useful services may be drastically reduced (TEEB, 2010).

The review by Burley et al. (2012) of the wetlands of South East Queensland, Australia, indicates that adaptations focused on wetland and biodiversity conservation may impact urban form in coastal areas. A study of changes in tree species composition, diversity, and distribution across old and newly established urban parks in Bangalore, India, aims to find ways to increase ecological benefits from these biodiversity hotspots (Nagendra and Gopal, 2011). When Leipzig applied a new approach to evaluating the impacts on local climate of current land uses and proposed planning policies, using evapotranspiration and land surface emissivity as indicators, green areas and water surfaces were found to have cooling effects, as expected, but some policies increased local temperatures (Schwarz et al., 2011).

Some aspects of mitigating climate change in urban areas requires a dense urban form to maximize agglomeration economies in more efficient resource use and waste reduction and to reduce urban expansion, reliance on motorized transport, and building energy use. But adaptation may require an urban form that favors green infrastructure and open space for storm water management, species migration, and urban cooling (Hamin and Gurran, 2009; Mees and Driessen, 2011). Higher densities can prevent the maintenance of ecologically viable systems with high biodiversity and exacerbate the urban heat island, in turn generating the need for more cooling, increasing energy use, and further escalating the urban heat island effect. This is the "density conundrum" (Hamin and Gurran, 2009, p. 242): At what point are densities too high to maintain ecologically viable systems with high biodiversity, especially given that urbanization has already compromised the ability of ecosystems to buffer urban development from hazards? This situation will be further exacerbated by new hazards (e.g., floods, fires) to which systems are or will be exposed as the result of climate change (Depietri et al., 2012).

8.3.3.7.1. Green and white roofs

Green and white roofs, introduced in a range of cities, have the potential to create synergies between mitigation and adaptation. Rooftop vegetation helps decrease solar heat gain while cooling the air above the building (Gill et al., 2007), thus improving the building's energy performance (Mees and Driessen, 2011; Parizotto and Lamberts, 2011). It can reduce cooling demand and often the use of air conditioning with its local contribution to heat gain and its implications for GHG emissions (Jo et al., 2010; Zinzi and Agnoli, 2012). Rooftop vegetation can also retain water during storms, reducing stormwater runoff (Voyde et al., 2010; Palla et al., 2011; Schroll et al., 2011) and promoting local biodiversity and food production. Studies have compared the performance of living roofs across different plant cover types, levels of soil water, and climatic conditions (see, e.g., Simmons et al., 2008; Jim, 2012). Hodo-Abalo et al. (2012) confirm that a dense foliage green roof has a greater cooling effect on buildings in Togolese hot-humid climate conditions. Several field experiments combined with simulated modeling of impacts in the USA also confirm the positive thermal behavior of green roofs compared to alternative roof coverings (e.g., Getter et al., 2011; Scherba et al., 2011; Susca et al., 2011). Durban has a pilot green roof project on a municipal building; indigenous plants are being identified for the project and rooftop food production is being investigated (Roberts, 2010). New York's lack of space for street-level planting helped encourage the

adoption of living roofs (Corburn, 2009). Under its Skyrise Greenery project, Singapore has provided subsidies and handbooks for rooftop and wall greening initiatives (Newman, 2010). Based on field tests in the UK, Castleton et al. (2010) find that older buildings with poor insulation benefit more from green roofs than newer structures built to higher insulation standards. Wilkinson and Reed (2009) suggest that the overshadowing caused by buildings in city centers may mean lower potential for green roof retrofits compared to installations in suburban areas and smaller towns with lower rise buildings. Benvenuti and Bacci (2010) highlight the availability of water as the main limiting factor in the realization of green roofs.

A recent meta-analysis suggests that green roofs and parks may have limited effects on cooling. Findings on green roofs were mixed; some studies, but not all, showed lower temperatures above green sections. An urban park was found to be about 1°C cooler than a non-green site and larger parks had a greater cooling effect. Yet studies were mainly observational, lacking rigorous experimental designs. It remains unclear whether there is a simple linear relationship between a park's size and its cooling impact (Bowler et al., 2010) .

Cool roofs or white reflective roofs use bright surfaces to reflect shortwave solar radiation, which lowers the surface temperature of buildings compared to conventional (black) roofs with bituminous membrane (Saber et al., 2012). There is also some work on roads and pavements with increased reflectivity (Foster et al., 2011b). Some studies have quantified the cooling benefits from white roofs in various urban settings—in Hyderabad (Xu et al., 2012), in Sicily (Romeo and Zinzi, 2011), and in the North American climate (Saber et al., 2012). Comparisons between green and white roofs have also been undertaken. Ismail et al. (2011) investigated their cooling potential on a single-story building in Malaysia, and Zinzi and Agnoli (2012) explored the difference in a Mediterranean climate. Results suggest that local conditions play a dominant role in determining the best treatment. Hamdan et al. (2012), for instance, found a layer of clay on top of the roof as the most efficient for passive cooling purposes in Jordan, compared to two different types of reflective roofs.

8.3.3.8. Adapting Public Services and Other Public Responses

As city risk and vulnerability assessments become more common and detailed, they provide a basis for assessing how policies and services can adapt. Section 8.2 noted health impacts that can arise or be exacerbated by climate change that will increase demands on health care systems—including those linked to air pollution, extreme weather, food or water contamination, and climate-sensitive disease vectors. For air quality, additional research is still needed to understand the complex links between weather and pollutants in the context of climate change (Harlan and Ruddell, 2011). Important synergies can be achieved through combining mitigation and adaptation strategies to improve air quality, reduce private transport, and promote healthier lifestyles (Harlan and Ruddell, 2011; see also Bloomberg and Aggarwala, 2008).

In responding to disasters, health care and emergency services (including ambulance, police, and fire fighting) will have increased workloads while also ensuring that their systems can adapt. Their effectiveness can be enhanced by good working relationships with other key government sectors and with civil protection services including the army and the Red Cross/Red Crescent national societies. For cities without a robust early warning system or an emergency response network, adapting to climate change may require significant improvements in staffing, resources, and preparedness plans, for example, the data and personnel to deal with vulnerable residents during heat waves. Particular attention may be required to provide emergency services for informal settlements lacking adequate roads or infrastructure and, when needed, evacuation plans for all those that have to move. There is little evidence of consideration to changes in services in response to climate change in the city case studies listed in Box 8-1.

Enhanced emergency medical services may help cope with extreme events while health officials can also improve surveillance, forecast the health risks and benefits of adaptation strategies, and support public education campaigns. Public health systems may need to increase attention to disease vector control (e.g., screening windows, eliminating breeding grounds for the mosquitoes that are vectors for malaria and dengue) and bolster food hygiene measures linking to increased flooding and temperatures. The costs of adapting health care systems may be considerable—for instance, modifying buildings and equipment, training staff, and setting up comprehensive surveillance and monitoring systems that can capture the health risks of climate change, as well as other risks.

Schools and day-care centers may need risk and vulnerability assessments. School buildings can be designed and built to serve as safe shelters during floods or storms to which those at risk can move temporarily—although it is also important after a disaster to quickly reestablish functioning schools both for the benefit of children and their parents (Bartlett, 2008).

8.4. Putting Urban Adaptation in Place: Governance, Planning, and Management

This section discusses what we have learned about introducing adaptation strategies into the decision processes of urban governments, households, communities, and the private sector. Many aspects of adaptation can be implemented only through what urban governments do, encourage, allow, support, and control. This necessarily involves overlapping responsibilities and authority across other levels of government as well (Dietz et al., 2003; Ostrom, 2009; Blanco et al., 2011; Corfee-Morlot et al., 2011; McCarney et al., 2011; Kehew et al., 2013). Approaches include new urban policies and incentives for action, as well as ensuring that existing policies reduce risk and vulnerability (Urwin and Jordan, 2008; Bicknell et al., 2009; Brugmann, 2012). Transformation should be considered where fundamental change to economic, regulatory, or environmental systems is seen as the most appropriate mechanism for reducing risk and where maintaining existing systems offers little scope for adaptation (Pelling and Manuel-Navarrete, 2011), for instance resettlement or abandonment of previously developed land.

City governments that have developed adaptation policies recognize the value of an iterative process responsive to new information, analyses, or frameworks (National Research Council, 2010). In a range of cities,

it has proved useful to have a unit responsible for this within city government, drawing together relevant data, informing key politicians and civil servants, encouraging engagement by different sectors and departments, and consulting with key stakeholders (Roberts, 2010; Brown et al., 2012).

The capacity of local authorities to work effectively, alone or with other levels, is constrained by limited funding and technical expertise, institutional mechanisms, and lack of information and leadership (Gupta et al., 2007; Carmin et al., 2013). Established development priorities and planning practices in functions like land-use, construction, or infrastructure provision may not be aligned with the goals or practice of adaptation (Ostrom, 2009; Pelling, 2011a; Garschagen, 2013). Many national governments face comparable constraints and still do not recognize the importance of local governments in adaptation (OECD, 2010). Local adaptive capacity can benefit from disaster risk reduction (Schipper and Pelling, 2006; UNISDR, 2008). New national legislation and institutions on disaster risk reduction have helped in some cases to strengthen and support local government capacity (Section 8.3.2.2), but as with other forms of adaptation, they require budgetary support and an increase in local professional capacities to be effective locally (Johnson, 2011).

8.4.1. Urban Governance and Enabling Frameworks, Conditions, and Tools for Learning

Enabling conditions and frameworks to support urban adaptation are grounded in institutional structures, values and local competence, interest, awareness, and analytical capacity (Moser and Luers, 2008; Birkmann et al., 2010). Preconditions for sound adaptation decision making relate to principles of good urban government (what government does) and governance (how they work with other institutions and actors including the private sector and civil society) (OECD, 2010; Bulkeley et al., 2011; Garschagen and Kraas, 2011). This includes science-policy deliberative practice and vulnerability assessment (National Research Council, 2007, 2008, 2009; Renn, 2008; Adger et al., 2009; Kehew, 2009; Moser, 2009; Corfee-Morlot et al., 2011). Civil society has important roles, for instance through community risk assessment, and the incorporation of local knowledge, preferences, and norms (Tompkins et al., 2008; van Aalst et al., 2008; Shaw et al., 2009; Fazey et al., 2010; Krishnamurthy et al., 2011). Human behavior, values, and social norms have a role and can evolve through dialog and understanding (Dietz et al., 2003; Moser, 2006; Ostrom, 2009), and engagement with stakeholders over time is key to effective adaptation (Bulkeley et al., 2011; Kehew et al., 2013). This has to allow consideration of dominant development trajectories and alternatives that can be approached by transformative adaptation. The capacity to act within urban settings varies with the organizational context for development (Section 8.1, Table 8-2), including the level of decentralization (Blanco et al., 2011; Corfee-Morlot et al., 2011; McCarney et al., 2011).

8.4.1.1. Multi-Level Governance and the Unique Role of Urban Governments

A framework for urban governance emerges from the challenges that climate change brings to multilevel risk governance. Figure 8-4 summarizes key actors and their relationships. Here, knowledge, policy, and action are produced through the interaction, across scales, of three kinds of actors (based on Corfee-Morlot et al., 2011):

- Knowledge producers (academic science, community, business, and non-governmental organization (NGO) produced research)
- Knowledge actors or users (most important here is local government often in collaboration with partners)
- Knowledge filters who can mediate between knowledge production and action (the media, lobby groups, and boundary organizations that help in translation) (Carvalho and Burgess, 2005; Leiserowitz, 2006; Ashley et al., 2012).

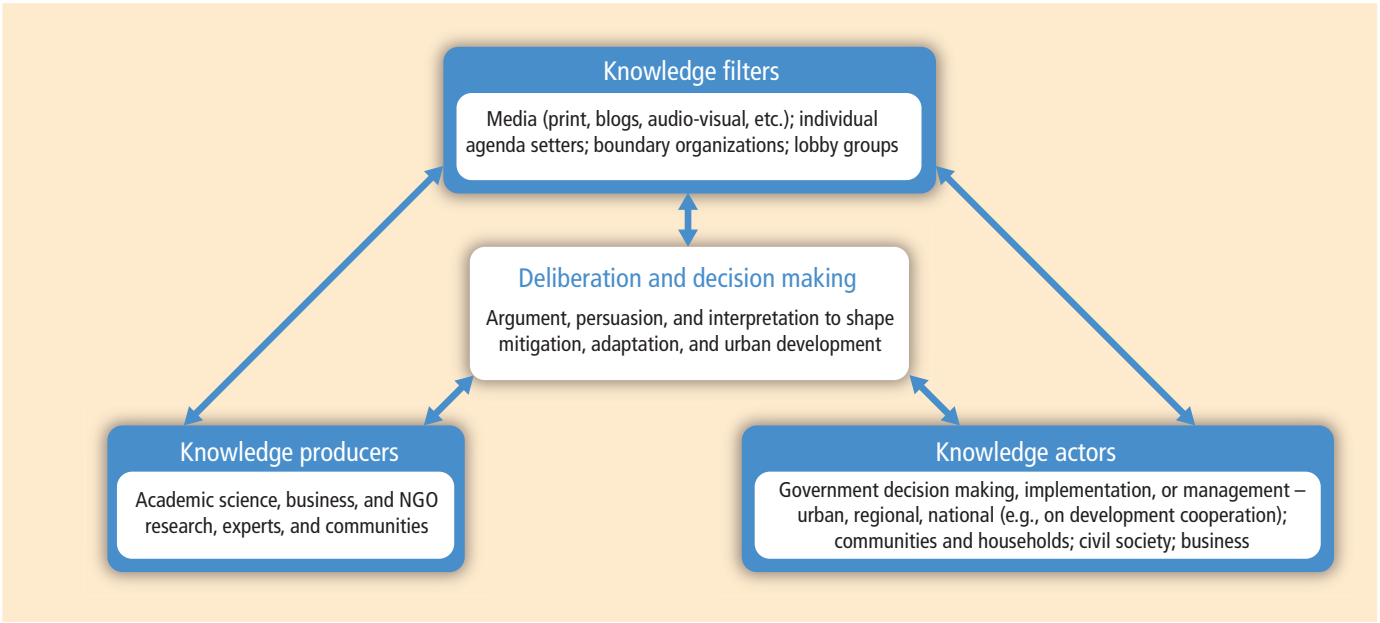


Figure 8-4 | The co-production of knowledge and policy for adaptation, mitigation, and development in urban systems (adapted from Corfee-Morlot et al., 2011).

Urban governments, provided with authority for relevant policy decisions, are central to this process (Blanco et al., 2011; Corfee-Morlot et al., 2011; McCarney, 2012; Kehew et al., 2013). Good practice also hinges in part upon the credibility, legitimacy, and salience of science policy processes; a strong local evidence base of historical and projected data on climate change; and ongoing, open processes to support dialog between government, civil society, and expert advisors (Cash and Moser, 2000; Cash et al., 2006; National Research Council, 2007; Preston et al., 2011; Kehew et al., 2013; see also Chapter 2). Timely and salient communication is important where a key role is played by the media, lobby groups, and boundary organizations that "translate" scientific or expert information for local communities and sometimes also help to shape the questions of scientific inquiry (Jasanoff, 1998; Gieryn, 1999; Moser, 2006; Moser and Dilling, 2007; Moser and Luers, 2008). Good governance facilitates the mediation of policy and decision processes across these different actors, spheres of influence, sources of information, and resources, to co-produce knowledge and support learning and action over time.

While urban governments have authority for many relevant adaptation decisions, they can be enabled, bounded, or constrained by national, subnational, or supranational laws, policies, and funding and land use and infrastructure planning decisions (OECD, 2010; Brown, 2011; Carter, 2011; Martins and da Costa Ferreira, 2011; Arup and C40, 2012; Kehew et al., 2013). This includes establishing formal mandates for urban adaptation action, without which adaptation becomes optional or discretionary, dependent on local-level interest and resources, and particularly vulnerable to leadership change. Where mandates for adaptation exist, they have been important in driving local level action (Kazmierczak and Carter, 2010). New mandates (formal or informal) may also require institutional changes (Roberts, 2008; Lowe et al., 2009; Kazmierczak and Carter, 2010).

The level of complexity is raised in large metropolitan areas, especially when they are growing rapidly. Action has to be coordinated and harmonized across multiple urban jurisdictions; often dozens of them (e.g., Mexico City, São Paulo, London, and Buenos Aires) and occasionally hundreds (e.g., Abidjan and Tokyo) (McCarney et al., 2011; McCarney, 2012), for instance to implement flood protection of contiguous land areas (Hallegatte et al., 2011b). Although there is some evidence of innovative responses at subnational levels to plan for extreme weather events and climate change, limited capacity and experience at local government level suggests the need for support from higher levels of government (Norman and Nakanishi, 2011; EEA, 2012; Gurran et al., 2012).

Policies and incentives need to be aligned to work coherently across multiple levels of government to define and deliver effective urban adaptation. This often involves institutions at different levels with different scopes of authority (Young, 2002; Bulkeley and Kern, 2006; Cash et al., 2006; Mukheibir and Ziervogel, 2007; Urwin and Jordan, 2008; Kern and Gotelind, 2009; Corfee-Morlot et al., 2011; EEA, 2012). Water authorities, for instance, may operate at water-basin level, representing both national and local interests while operating independently of urban authorities. Failing to ensure consistent alignment and integration in risk management can lock in outcomes that raise the vulnerability of urban populations, infrastructure, and natural systems even where pro-active adaptation policies exist (Urwin and Jordan, 2008; OECD, 2009; Benzie et al., 2011). Local government capacity is important, as well as the institutions that facilitate coordination across multiple, nested, poly-centric authorities with potential to mainstream adaptation measures and tailor national goals and policies to local circumstances and preferences. Horizontal coordination and networking across actors and institutions in different municipalities and metropolitan areas can accelerate learning and action (Aall et al., 2007; Lowe et al., 2009; Schroeder and Bulkeley, 2009).

Consultation and awareness-raising can help avoid the kind of public backlash that occurred when the French government sought to ban urban development and require strategic retreat in areas of risk to coastal flooding after the 2010 storm Xynthia (Laurent, 2010; Przyluski and Hallegatte, 2012). There can also be vested interests and trade-offs where near-term development conflicts with longer-term adaptation and resilience goals. Public engagement, openness, and transparency can help ensure democratic debate to balance public interests and longer-term goals against the short-term benefits of unconstrained development. Urban governments are uniquely situated to understand local contexts, raise local awareness, respond to citizens' and civil society pressures, and work to build an inclusive policy space (Grindle and Thomas, 1991; Brunner, 1996; Cash and Moser, 2000; Brunner et al., 2005; Healey, 2006). Urban governments can also promote understanding of climate change risk and help to create a common vision for the future (Moser, 2006; Moser and Dilling, 2007; Ostrom, 2009; Corfee-Morlot et al., 2011). The fact that preferences are more homogeneous within smaller units (Ostrom, 2009) provides opportunities for leadership and innovation that may not exist at higher levels of governance. Urban governments, so often responsible for a substantial share of urban infrastructure (Arup and C40, 2012; Hall et al., 2012), are also central to the interface between climate change and development, including provision for essential infrastructure and services (Bulkeley and Kern, 2006; Bulkeley, 2010). Urban planning structures, processes, and plans can integrate and mainstream adaptation plans and risk management into urban and sectoral planning with a clear time frame, mandate, and resources for implementation (Agrawala and Fankhauser, 2008; Bicknell et al., 2009; Brugmann, 2012), even if functional authority is at national or subnational regional levels (Hall et al., 2012). Many urban governments show growing awareness and analytical capacity in adaptation planning but there is less evidence in implementation and influence on key sectors (Roberts, 2010).

Local government decisions can be driven by short-term priorities of economic growth and competitiveness (Moser and Luers, 2008) and addressing climate change can mean taking a longer-term perspective (Leichenko, 2011; Pelling, 2011a; Romero-Lankao and Qin, 2011; Viguié and Hallegatte, 2012). Tension also exists between economic growth and the needs of the large, often growing, numbers of ill-served urban poor (Bicknell et al., 2009) whose resilience to climate change will depend on infrastructure and services. The challenges in low- and middle-income countries are exacerbated by relative inattention from international donors to urban policy and development concerns, as they have historically worked through national government planning processes, which may not capture the needs of urban populations (Mitlin and Satterthwaite, 2013). Donors may also prefer visible physical infrastructure projects over local institution and capacity-building investments. Most national governments in high-income countries also

have yet to fully embrace local adaptation initiatives (McCarney et al., 2011).

8.4.1.2. Mainstreaming Adaptation into Municipal Planning

Mainstreaming adaptation into urban planning and land use management and legal and regulatory frameworks is key to successful adaptation (Lowe et al., 2009; Kehew et al., 2013). It can help planners rethink traditional approaches to land use and infrastructure design based on past trends, and move toward more forward looking risk-based design for a range of future climate conditions (Kithiia, 2010; Solecki et al., 2011; Kennedy and Corfee-Morlot, 2013), as well as reducing administrative cost by building resilience through existing policy channels (Urwin and Jordan, 2008; Benzie et al., 2011; Blanco et al., 2011). Mainstreaming through local government policies and planning ensures that investments and actions by businesses and households contribute to adaptation (Kazmierczak and Carter, 2010; Sussman et al., 2010; Brown, 2011; Mees and Driessen, 2011). But this must avoid overloading already complex and inadequate planning systems with unrealistic new requirements (Roberts, 2008; Kithiia, 2010); particularly in many low- and middle-income countries, these systems are already stressed by lack of information, institutional constraints, and resource limitations.

Mainstreaming may best be initiated by encouraging pilot projects and supporting experimentation by key sectors within local government. Assigning responsibility to specific departments can make the adaptation (and mitigation) message easier to understand by local governments and other stakeholders and the associated responsibilities and actions clearer and simpler to identify and assign (Roberts, 2010; UN-HABITAT, 2011a; Roberts and O'Donoghue, 2013). Pilot projects and sectoral approaches ground adaptation in practical reality (Roberts, 2010; Tyler et al., 2010; UN-HABITAT, 2011a; Brown et al., 2012). As actors in each sector in local government come to understand their roles and responsibilities, the basis for integration and cross-sectoral coordination is formed.

The literature suggests that opportunities to mainstream climate change into urban planning and development are still largely missed (Sánchez-Rodríguez, 2009). The planning agenda can already be full (Measham et al., 2011). Challenges in information, institutional fragmentation, and resources (Sánchez-Rodríguez, 2009; Wilson et al., 2011) make it difficult to introduce the additional layer of climate change planning (Roberts, 2008; Kithiia, 2010), which may also be seen merely as "add-ons" (Kithiia and Dowling, 2010, p. 474).

Other challenges also limit progress—for instance the lack of leadership and of focal points on urban adaptation (see Section 8.4.3.4 for more detail). In times of economic hardship (e.g., the current recession), local authorities with already limited resources may prioritize conventional economic and development goals over "environmental" issues including climate change adaptation (Shaw and Theobald, 2011; Solecki, 2012). A further challenge is getting the timely evaluation of emerging adaptation measures (Hedger et al., 2008; Preston et al., 2011).

Experience with adaptation programs show they are often more cross-sectoral, cross-institutional, and complex. They operate across a range of scales and timelines; are rooted in local contexts; involve many stakeholders; and include high levels of uncertainty (Roberts et al., 2012; Roberts and O'Donoghue, 2013). Standardized guidelines for action are less relevant and urban adaptation practitioners have identified instead the need for "clarity, creativity, and courage" (ICLEI Oceania, 2008, p. 62). In all instances, where progress on adaptation planning is observed, local leadership is a central factor (Carmin et al., 2009, 2013; Measham et al., 2011).

8.4.1.3. Delivering Co-Benefits

Important opportunities also exist to combine adaptation and mitigation goals in urban housing policies (and the energy sources they draw on), infrastructure investments, and land use decisions—especially in high- and middle-income countries (Satterthwaite, 2011). Co-benefits for mitigation and for transformation require a reconsideration of dominant development pathways and of possible alternatives both within and beyond the urban core, influencing, for instance, local environments along with water basin management and coastal defense regimes (Urwin and Jordan, 2008; OECD, 2010). Examples of positive and negative interactions between urban adaptation and mitigation strategies suggest that these strategies will need to be assessed and managed to achieve co-benefits (Viguié and Hallegatte, 2012; Kennedy and Corfee-Morlot, 2013). Viguié and Hallegatte (2012) demonstrate that despite trade-offs, careful planning can yield adaptation-mitigation co-benefits across greenbelt policies, flood zoning, and transportation policies. Local governments may be able to address both adaptation and mitigation using pre-existing tools and policies such as building standards, transport infrastructure planning, and other urban planning tools (Hallegatte et al., 2011a). It may be possible to avoid or limit trade-offs by developing institutional links between the different policy areas at the level of local planning (Swart and Raes, 2007; Viguié and Hallegatte, 2012; Kennedy and Corfee-Morlot, 2013).

Adaptation can produce development co-benefits in urban areas including safer, healthier, and more comfortable urban homes and environments and reduced vulnerability for low-income groups to disruptions in their incomes and livelihoods (Kousky and Schneider, 2003; Bicknell et al., 2009; Burch, 2010; Clapp et al., 2010; Roberts, 2010; Anguelovski and Carmin, 2011;Hallegatte et al., 2011a). Local development co-benefits may be particularly important to highlight in low- and middle-income countries, where lack of policy buy-in accompanies limited local capacity (UN-HABITAT, 2011a) and where current climate change challenges appear marginal compared with development deficits (Roberts, 2008; Kithiia and Dowling, 2010; Kiunsi, 2013). Urban authorities in India can see adaptation as a priority if it also addresses development and environmental health concerns (Sharma and Tomar, 2010).

Development and climate change adaptation are often seen as separate challenges in a subnational planning context. A review in OECD countries showed only Japan and South Korea championing climate action as integral to subnational development planning, although Finland and Sweden have innovative subnational climate policies and action programs funded by central government (OECD, 2010). For most OECD countries, urban development and adaptation are tackled separately. Yet policy research finds that successful adaptation is rooted within and harmonized

with such development priorities as poverty reduction, food security, and disaster risk reduction (Moser and Luers, 2008; Bicknell et al., 2009; Measham et al., 2011).

8.4.1.4. Urban Vulnerability and Risk Assessment Practices: Understanding Science, Development, and Policy Interactions

A critical aspect of urban climate risk governance is the integration of scientific knowledge into decision making, building on exchange among scientists, policymakers, and those at risk (Vescovi et al., 2007; National Research Council, 2009; Government of South Africa, 2010; Rosenzweig and Solecki, 2010). International policy advisory agencies with an interest in urban adaptation can augment this (Sonover et al., 2007; ICLEI, 2010), but will depend on local capacity and engagement to produce, access, and use climate change information and processes (Hallegatte et al., 2011a; Carmin et al., 2013). Local and regional boundary organizations can be influential in making scientific and technical information more salient to decision makers (Bourque et al., 2009; Corfee-Morlot et al., 2011). In many instances, key boundary functions are carried out by nearby academic or research communities and these can also be a source of leadership for urban adaptation (Sánchez-Rodríguez, 2009; Government of South Africa, 2010).

Even where detailed vulnerability or risk assessments exist, their influence may be limited if decision makers do not access and use this information. Urban master plans or strategic plans with a time horizon of 10 or more years can incorporate climate risks and vulnerabilities, but assessments must be available to influence such plans. Moser and Tribbia (2006), exploring how decision makers access and use information, find that resource managers tend to rely more on informal sources (maps or in-house experts, media, and Internet) than on scientific journals. This reinforces the point made earlier in regard to producers of scientific and information and knowledge actors to needing to work closely with decision makers in the production and communication of scientific information (Cash et al., 2003, 2006; Moser, 2006; Corfee-Morlot et al., 2011).

8.4.1.5. Assessment Tools: Risk Screening, Vulnerability Mapping, and Urban Integrated Assessment

Assessments of risk and vulnerability to the direct and indirect impacts of climate change are often the first step in getting government attention, especially when put in the context of development policy objectives (Hallegatte et al., 2011a; Mehrotra et al., 2011a; see also Section 8.2). Including risk management information in infrastructure design at the planning or design phase can mean lower retrofit costs later on (Baker, 2012; World Bank, 2012). A variety of planning and assessment tools can be helpful, including impact assessment, environmental audits, vulnerability mapping, disaster risk assessment and management tools, local agenda 21 plans, and urban integrated assessment as part of public investment planning and as used by community organizations (Haughton, 1999; UN-HABITAT, 2007; Baker, 2012). Governments can ensure that up-to-date climate information is available to the private sector to support adaptation (Agrawala et al., 2011; see also Section 8.4.2.3). Some of these tools provide entry points and a means for participatory engagement, but often give little consideration to adaptation (Gurran et al., 2012). More reliable, specific, and downscaled projections of climate change and tools for risk screening and management can help engage relevant public sector actors and the interest of businesses and consumers (AGF, 2010a; UNEP, 2011).

Local climate change risk assessments, vulnerability, and risk mapping can identify vulnerable populations and locations at risk and provide a tool for urban adaptation decisions (Ranger et al., 2009; Hallegatte et al., 2011a; Livengood and Kunte, 2012; Kienberger et al., 2013). The LOCATE methodology (Local Options for Communities to Adapt and Technologies to Enhance Capacity), which integrates hazard and vulnerability mapping to inform choices about which populations, infrastructure, and areas to prioritize for action (Annecke, 2010) is being tested in eight African countries; in each, an NGO is working with communities on across-project design and implementation, monitoring, evaluation, and learning.

Tools that organize and rank information on vulnerability in different locations often aim to identify relative and absolute differences in risk and resilience capacity (Milman and Short, 2008; Hahn et al., 2009; Posey, 2009; Manuel-Navarrete et al., 2011). They vary from quick screenings to fuller risk analyses and evaluations of adaptation options (Hammill and Tanner, 2011). Preston et al. (2011), noting the wide variety of functions and methods in 45 vulnerability mapping studies, suggest that effectiveness is guided by identifying clear goals, robust technical methods, and engagement of the appropriate user communities. Halsnæs and Trærup (2009) recommend the use of a limited set of indicators; engagement with representatives of local development policy objectives; and a stepwise approach to address climate change impacts, development linkages, and economic, social, and environmental dimensions. Methods for application across scale (Kienberger et al., 2013), considering the urban environment as a system, allow for better understanding of interconnections between root causes, risk production, cascading impacts, and vulnerabilities (Kirshen et al., 2008; UNISDR, 2011; da Silva et al., 2012).

Downscaling of climate scenarios, systems models, and urban integrated assessment modelling at local scales integrate information in a forward-looking framework to support urban policy assessment (e.g., van Vuuren et al., 2007; Dawson et al., 2009; Hall et al., 2010; Hallegatte et al., 2011a; Walsh et al., 2011; Viguié and Hallegatte, 2012). Integrated assessment modelling considers the driving forces of urban vulnerability and climate change impacts alongside possible policy responses and their outcomes. By integrating knowledge, this provides a tool for policy makers to examine and better understand synergies and trade-offs across policy strategies (Dawson et al., 2009; Viguié and Hallegatte, 2012). These modeling frameworks take time to build and to be incorporated into decision-making processes. Although early results are promising, they also highlight the difficulty of producing tools that can be easily used by local governments (e.g., see also Hall et al., 2012; Walsh et al., 2011, 2013).

Despite growing attention, useful assessment of climate change at urban spatial scales is generally lacking (Hunt and Watkiss, 2011). A small number of cities, largely in high-income countries, have quantified

Frequently Asked Questions

FAQ 8.4 | Shouldn't urban adaptation plans wait until there is more certainty about local climate change impacts?

More reliable, locally specific, and downscaled projections of climate change impacts and tools for risk screening and management are needed. But local risk and vulnerability assessments that include attention to those risks that climate change will or may increase provide a basis for incorporating adaptation into development now, including supporting policy revisions and more effective emergency plans. In addition, much infrastructure and most buildings have a lifespan of many decades so investments made now need to consider what changes in risks could take place during their lifetime. The incorporation of climate change adaptation into each urban center's development planning, infrastructure investments and land use management is well served by an iterative process within each locality of learning about changing risks and uncertainties that informs an assessment of policy options and decisions.

local climate change risks; even fewer have quantified possible costs under different scenarios. Some exceptions exist: Durban has developed a benefit-cost model for adaptation options (Cartwright et al., 2013), and there have been urban climate risk assessments in low- or middle-income developing countries as part of targeted development cooperation programs, supported by external partners (World Bank, 2011, 2013). Sea level rise and coastal flood risk, health, and water resources are among the most studied sectors; energy, transport, and built infrastructure get far less attention (Hunt and Watkiss, 2011; World Bank, 2011, 2013; Roy et al., 2012). Science and climate change information is increasingly available, but socioeconomic drivers of vulnerability and impacts, and opportunities and barriers to adaptation are less well studied and understood (Measham et al., 2011; Romero-Lankao and Qin, 2011).

8.4.2. Engaging Citizens, Civil Society, the Private Sector, and Other Actors and Partners

8.4.2.1. Engaging Stakeholders in Urban Planning and Building Decision Processes for Learning

A common vision of a future resilient, safe, and healthy city can be the first step to achieving it (Moser, 2006; Moser and Dilling, 2007; Corfee-Morlot et al., 2011; UN-HABITAT, 2011a). Participatory processes figure prominently in cities that have been leaders in urban adaptation (Rosenzweig and Solecki, 2010; Brown et al., 2012; Carmin et al., 2012b). The conceptual literature agrees that participatory decision making is essential where uncertainty and complexity characterize scientific understanding of policy problems (Funtowicz and Ravetz, 1993; Liberatore and Funtowicz, 2003). Many have argued that the institutional features of the risk management decision-making process—participatory inclusiveness, equity, awareness raising, deliberation, argument, and persuasion—will determine the legitimacy and effectiveness of action (Dietz et al., 2003; Lim et al., 2004; Mukheibir and Ziervogel, 2007; Corfee-Morlot et al., 2011). Yet the review of 45 vulnerability mapping exercises found that only 40% included stakeholder participation, raising questions about the legitimacy and salience of contemporary approaches (Preston et al., 2011). It also highlights the challenge local governments face to garner resources, including technical expertise and institutional capacity, to organize and use participatory processes to strengthen rather than delay adaptation decision making (Carmin et al., 2013).

In many urban settings, civil society and the private sector already have significant and positive roles in support of adaptation planning and decisions. Some studies show that despite limited information, adaptation at urban scale is moving ahead, particularly through initial planning and awareness raising (Lowe et al., 2009; Anguelovski and Carmin, 2011; Hunt and Watkiss, 2011). Experience in a handful of cities—for example, Cape Town, Durban, London, New York—shows that a wide number and variety of engaged stakeholders at early stages in a risk assessment creates political support and momentum for follow-up research and adaptation planning (Rosenzweig and Solecki, 2010; Anguelovski and Carmin, 2011; Hunt and Watkiss, 2011). In informal settlements with little or no formal infrastructure and services, stakeholder engagement is a means for participatory community risk assessment, where local adaptive capacity is built in part through local knowledge (Livengood and Kunte, 2012; Kiunsi, 2013). Over time, institutional mechanisms can be built that support innovation, collaboration, and learning within and across sectors to advance urban adaptation action, but it takes time and resources (Mukheibir and Ziervogel, 2007; Burch, 2010; Roberts, 2010; Anguelovski and Carmin, 2011).

8.4.2.2. Supporting Household and Community-Based Adaptation

In well-governed cities, community groups and local governments are mutually supportive, providing information, capacity, and resources in maintaining local environmental health and public safety, which in turn can support adaptation. Where local government has not yet formulated an adaptation strategy, community groups can raise political visibility for climate risks and provide front-line coping (Wilson, 2006; Granberg and Elander, 2007), and also begin to address gender disparities in urban risks (Björnberg and Hansson, 2013).

The full range of infrastructure and services needed for resilience is generally affordable only in middle- and upper-income residential developments in low- and lower-middle income countries. In most cities and neighborhoods, where infrastructure coverage is incomplete and household incomes limited, community organizations—or community-

based adaptation—offer a rich resource of adaptive capacity to cope and to prepare for future risk. A range of studies document the depth of knowledge and capacities held by local populations around reducing exposure and vulnerability (Anguelovski and Carmin, 2011; Dodman and Mitlin, 2011; Livengood and Kunte, 2012). For a high proportion of the households that live in informal urban settlements, household and community-based adaptation is their only means of responding to risk. They are well used to coping with environmental hazards (Wamsler, 2007; Adelekan, 2010; Jabeen et al., 2010; Livengood and Kunte, 2012; Kiunsi, 2013). Some seek to modify hazards or reduce exposure—for example, through ventilation and roof coverings to reduce high temperatures; barriers to prevent floodwater entering homes; keeping food stores on top of high furniture; and moving temporarily to safer locations (Douglas et al., 2008). A study in Korail, one of Dhaka's largest informal settlements, showed the range of household responses to flood risk (see Figure 8-5). These include barriers across door fronts, increasing the height of furniture, building floors or shelves above the flood line, and using portable cookers (Jabeen et al., 2010). Provision for ventilation, creepers, or other material on roofs and false ceilings helped to keep down temperatures. These are important near-term adaptations, and there are similar responses in many informal settlements (e.g., Adelekan, 2010; Kiunsi, 2013), but they do not generate capacity to adapt to future risk.

There are multiple constraints on action for low-income households. Even where there are early warnings, a lack of trust in the security of their property and the right to return, along with fears for personal safety in shelters, are deterrents against evacuation (Jabeen et al., 2010; Hardoy et al., 2011). Tenants and those with the least secure tenure are often among the most vulnerable and exposed to hazards but also are usually unwilling to invest in improving the housing they live in and less willing to invest in community initiatives. Community-based responses are often reactive, addressing current more than future risks, though they may embody alternative development values and support local transformation. Shifting the burden of adaptation to the community level alone is unlikely to bring success. There are limits to what community action can do in urban areas. For instance, communities may build and maintain local water sources, toilets, and washing facilities or construct or improve drainage (see for instance the programs in cities in Pakistan described in Hasan, 2006) but they can neither provide the network infrastructure on which these depend (e.g., the water, sewer, and drainage mains and water treatment) nor can they improve city-region governance (Bicknell et al., 2009). Work on cities in the Caribbean and Latin America indicates the need for supportive links to community networks and/or local government for community-level adaptation to be effective (Pelling, 2011b; Mitlin, 2012).

There is some recognition that strengthening the asset base of low-income households helps increase their resilience to stresses and shocks, including those related to climate change (Moser and Satterthwaite, 2009). It has become more common for local governments to work with community-based organizations in upgrading their homes and settlements in disaster risk reduction (UNISDR, 2009, 2011; IFRC, 2010; Pelling, 2011b), and community-based adaptation is building on these experiences and capacities (Archer and Boonyabancha, 2011; Carcellar et al., 2011). Communities can have close relationships with formal state and market institutions, shaping subsequent adaptive capacity for members. Most housing and infrastructure upgrading programs mean that those living in low-income settlements become incorporated into "the formal" city and this often means an increased expectation on the state to reduce vulnerability, including long-term and strategic adaptation investments through access to schools, health care, infrastructure, and safety nets (Ferguson and Navarrete, 2003; Imparato and Ruster, 2003; Boonyabancha, 2005; UN Millennium Project, 2005; Fernandes, 2007; Almansi, 2009).

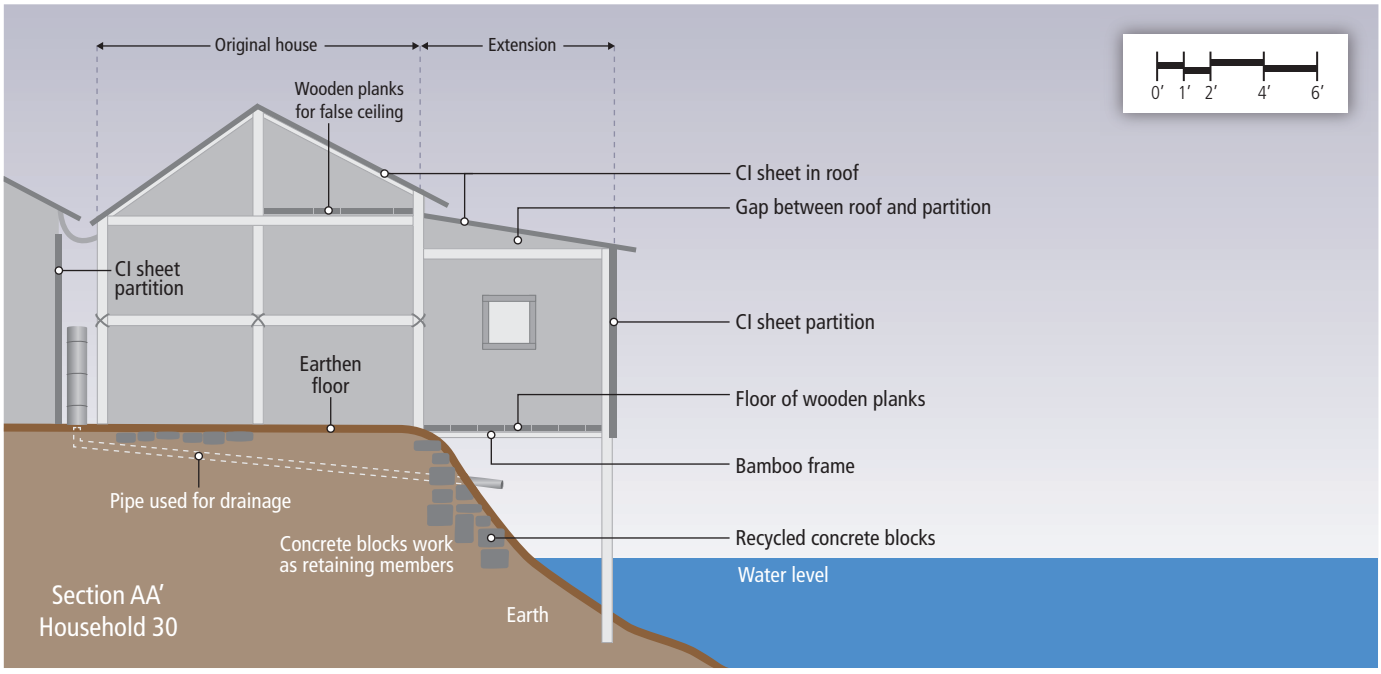


Figure 8-5 | Household adaptation—a cross-section of a shelter in an informal settlement in Dhaka (Korail) showing measures to cope with flooding and high temperatures (Jabeen et al., 2010). CI = corrugated iron.

There can still be obstacles. Where climate change or disaster risk is seen as distant or low probability, the immediate pressures of poverty tend to dominate local agendas (Banks et al., 2011). In many informal settlements, the issue of land tenure is also difficult to resolve and impedes upgrading programs (Boonyabancha, 2005, 2009; Almansi, 2009) and thus local-level adaptation action.

In a growing number of cities, residents' organizations supported by grassroots leaders and local NGOs are mapping and enumerating their informal settlements with eventual support and recognition from city governments (Patel and Baptist, 2012). This provides the data and maps needed to plan the installation or upgrading of infrastructure and services. Some of these enumerations also collect data on risks and vulnerabilities to extreme weather and other hazards (UN-HABITAT, 2007; Carcellar et al., 2011; Pelling, 2011b; Livengood and Kunte, 2012). For example, community surveys in the Philippines identified at-risk communities under bridges, in landslide-prone areas, on coastal shorelines and river banks, near open dumpsites, and in flood-prone locations (Carcellar et al., 2011). This mapping raises awareness among inhabitants of the risks they face, as well as getting their engagement in planning risk reduction and making early warning systems and emergency evacuation effective (Pelling, 2011b). Table 8-4 illustrates the contemporary limits of community-based action across key sites of coping and adaptation—highlighting where strategic partnerships, especially with a supportive municipal government, have key advantages.

IFRC (2010) identifies three broad requirements for successful urban community-based disaster risk reduction that can be extended to assess coping and adaptive capacity: the motivation and partnership of stakeholders; community ownership, with flexibility in project design; and sufficient time, funding, and management capacity. The effectiveness of community-based action also depends on how representative and inclusive the community leaders and organizations are (Appadurai, 2001; Wamsler, 2007; Banks, 2008; Houtzager and Acharya, 2011; Mitlin, 2012); their capacity to generate pressure for larger changes within government; and the relations between community organizations and government (Boonyabancha and Mitlin, 2012). Community-based adaptation can support transformation where it engages with key development agendas to reduce poverty and vulnerability (Sabates-Wheeler et al., 2008), and can address local inequalities and adverse power relations at district, city, national, and transnational levels (Mohan and Stokke, 2000). But urban governance regimes are often resistant to change and civil society organizations can be marginalized or co-opted, reducing the scope for transformative adaptation (Pelling and Manuel-Navarrete, 2011).

8.4.2.3. Private Sector Engagement and the Insurance Sector

Cities are attractive to private enterprises because so much business activity, private investment, and demand are concentrated there. Private enterprises generally favor cities with functioning city infrastructure and a wide range of services. As noted earlier, much investment for sound adaptation will need to come from households and firms of all sizes (Agrawala and Fankhauser, 2008; Bowen and Rydge, 2011). Brugmann (2012) argues that effective adaptation depends on catalyzing market-based investments. Beyond acting to protect their own interests, businesses are stakeholders in urban decision making, positioned to exploit new opportunities that arise from climate change (Chapter 14; see also Khattri et al., 2010). Private service providers and professional associations—including architects, engineers, and urban planners—can influence the pace and quality of adaptation efforts where an understanding of climate change is part of professional training and knowledge (McBain et al., 2010). Even when considering more political

Table 8-4 | The possibilities and limitations of focused activity for community groups on climate change coping and adaptation.

Capacity/focus of action	Coping: drawing on existing resources to reduce vulnerability and hazardousness and contain impacts from current and expected risk.	Adaptation: using existing resources and especially information to reorganize future asset profiles and entitlements to better position the household in light of anticipated future risk, and to prepare for surprises.
Physical: buildings and critical community-level infrastructure	Often possible to improve these although tenants will have little motivation to do so.	Limits in how much risk reduction is possible within settlement (i.e., without trunk infrastructure to connect to).
Physical: land and environment	Local hazard reduction through drain cleaning, slope stabilization, etc. is a common focus of community-based action (although there are fewer incentives where the majority of residents are short-term tenants or threatened with eviction).	External input required to design local hazard reduction works in ways that will consider the impacts of climate change 20 years or more in the future.
Social: health, education	Many examples of community-based action to improve local health and education access and outcomes, often with strong NGO and/or local government support.	Health care and education are amenable to supporting adaptation by providing long-term investments in capacity building. They are rarely framed in climate change adaptation terms.
Economic: local livelihoods	Livelihoods routinely assessed as part of household assessments of coping capacity in urban areas. More rarely is there a local livelihood focus for community-based coping.	Livelihoods and wider economic entitlements are key to individual adaptive profiles, but are seldom considered as part of urban community-based adaptation programs.
Institutional: community organization	Local community strengthening is a common goal of interventions aimed at building coping capacity. Risk mapping, early warning, risk awareness, community health promotion, and shelter training are common foci increasingly applied to urban communities. Local savings groups may have important roles.	Local community strengthening is a core element of planning for adaptation but there are few assessments of the medium-/long-term sustainability of outcomes. Where these have been undertaken, close ties to wider civil society networks or supportive local government were evident and these helped community organizations and actions to persist.
Institutional: external influence	It is unusual for coping programs to include an element of external advocacy aimed at changing policy or practices in local government.	Despite being core to determining future adaptation, there are very few examples of urban community based adaptation projects that include a targeted focus or parallel activity aimed at shifting priorities and practices in local government and beyond to support community capacity building.

Key: green = many cases of activity; amber = few cases of activity; red = very few cases of activity.

issues around the support of adaptation efforts (AGF, 2010b,c), most studies conclude that the need for adaptation investments will far exceed available funds from public budgets (Chapter 15; see also Agrawala and Fankhauser, 2008; World Bank, 2010d; Hedger, 2011).

For markets to favor urban adaptation, the private sector will need to see financial justification for involvement, for example, to ensure business continuity. A survey of companies on the most serious risks they faced (Aon, 2013) ranked weather/natural disasters 16th and climate change 38th although some higher ranked risks such as commodity prices (8th) or distribution/supply chain failure (14th) may be associated with climate change. Risk rankings differed by region (in Asia Pacific weather/natural disasters were 8th) and by sector (for agribusiness, weather/natural disasters were 2nd). Failure of climate change adaptation (as 'governments and business fail to enforce or enact effective measures to protect populations and transition businesses impacted by climate change') was listed by World Economic Forum (2013, p. 46) as one of the most likely environmental risks over the next 10 years and with having a high impact if the risk was to occur. Private sector actors may not be well positioned to consider the big adaptation questions, including changes in land use, development, and infrastructure planning (Redclift et al., 2011). For example, in Cancun, Mexico, close relationships between government and the corporate sector and the push for lucrative development have perpetuated an urban development model that generates climate change risk by increasing the hazard exposure of capital intensive, large-scale coastal development (Manuel-Navarrete et al., 2011). Without transformative change in urban development planning, private sector investments in adaptation will remain limited, such as designing buildings to withstand hurricanes but not tackling where development occurs. In the Cancun case, most investment comes from the state, for example, in beach replenishment and policies for rapid disaster recovery (Manuel-Navarrete et al., 2011).

The Private Sector Initiative of the UNFCCC Nairobi Work Programme offers support for businesses to integrate climate change science into their business planning, including in urban infrastructure and technology developments (http://unfccc.int/adaptation/nairobi_work_programme/private_sector_initiative/items/6547.php). This shows that both public and private (including civil society) actors can have a role in providing regional data and projections of socioeconomic trends, climate change, urban water supply and management practices, land use and building trends, and hazard mapping (UNEP, 2011). A review shows anecdotal evidence of large businesses investing in vulnerability assessments, yet few beginning to invest in adaptation (Agrawala et al., 2011). While some private sector actors take action against climate change risks, many postpone upfront investments for longer-term benefits against uncertain risks. Eakin et al. (2010) and Chu and Schroeder (2010) suggest that the private sector becomes more prominent when local governments and civil society action is limited, but this raises the issue of what incentives are required, especially in regard to low-income countries and communities.

Particularly in wealthier countries and communities, insurance markets can share and spread financial risk from climate change, for example, to help limit damages and manage risks in urban flood-prone areas (Rosenzweig and Solecki, 2010; see also Chapters 10 and 14). Risk-differentiated property insurance premiums can incentivize individuals and businesses to invest in adaption and retrofitting property or to avoid building in high-risk areas (Mills, 2007, 2012; Fankhauser et al., 2008). Relevant insurance instruments include health and life insurance for individuals; property and possession insurance for home and commercial property owners; and micro-insurance or micro-finance mechanisms to support those in low-income urban communities that are not covered by commercial insurance (see Box 8-3). Catastrophe bonds may be developed to cover some urban climate risks, but experience to date suggests they are quite narrowly written for specific events in specific locations, not providing the broad protection necessary to limit catastrophic risk in a changing climate and urban context (Keogh et al., 2011; Brugmann, 2012). Multicat Mexico 2009 is a catastrophe bond used to reinsure the Natural Disaster Fund covering the Mexican territory against hurricanes and earthquakes. This provides resources to mitigate losses up to US$50 million for hurricanes (Aragón-Durand, 2012). The insurance industry can also help shape urban adaptation initiatives, collaborating with building owners, developers, and governments to inform and encourage action.

Private investment or standard insurance markets will not protect low-income urban dwellers (Ranger et al., 2009; Hallegatte et al., 2010). For example, around half of Mumbai's population lives in informal settlements mostly without protective infrastructure and at increasing risk of flooding under most climate change scenarios (McFarlane, 2008; Hallegatte et al., 2010; Ranger et al., 2011). This population (and most of those living in informal settlements in other cities) will not be served by insurance because of the low ability to pay, high risks, and the high transaction costs for companies of administering many small policies. Low-income groups rely instead on local solidarity and government assistance when disaster hits (Hallegatte et al., 2010). In addition, where risk levels exceed certain thresholds, insurers will abandon coverage or set premiums unaffordable to those at risk. Insurance reduces the net risk and loss potential in urban areas, but can also increase inequality in security within neighborhoods or across cities unless coupled with government action to help manage risk in low-income communities (da Silva, 2010).

In many informal settlements, informal savings groups give members (mostly women) quick access to emergency loans (Mitlin, 2008). Where access to formal banking is limited, but social capital is high, those living in informal settlements have also pooled their savings for collective investments that reduce risk in their settlements or allow them to negotiate land and support for new homes (Manda, 2007; d'Cruz and Mudimu, 2013; Satterthwaite and Mitlin, 2014).

For the private sector to fulfill its potential to facilitate urban adaptation, public policy may need to establish enabling conditions in markets (see also Section 8.3), for example, targeting payment for provision of ecosystem services to deliver urban adaptation benefits that otherwise fall outside the market system. Such services include storm buffering and flood protection by paying for mangrove protection in coastal zones or urban green space along river-ways (Fankhauser et al., 2008; Roberts et al., 2012). In building construction, well-documented examples of market failure exist. Private investment in weather proofing new construction and retrofitting existing stock may fail to occur without regulatory intervention. This is an area where municipal governments often have authority to act. Public policy and funding is also needed to

8

Box 8-3 | Micro-finance for Urban Adaptation

Micro-finance schemes may contribute to pro-poor, urban adaptation through a variety of different instruments including micro-credit, micro-insurance, and micro-savings to help households and small entrepreneurs without access to formal insurance or commercial credit markets. These have been applied mostly in rural areas, usually benefitting those with some property (and thus not the poorest of rural populations). As Hammill et al. (2008, p. 117) state: "*The value MFS holds for climate change adaptation is in its outreach to vulnerable populations through a combination of direct and indirect financial support, and through the long-term nature of its services that help families build assets and coping mechanisms over time, especially through savings and increasingly through micro-insurance—products and sharing of knowledge and information to influence behaviours.*" Although typically more costly than commercial loans, micro-finance can support entrepreneurial undertakings by those unable to get bank loans, help diversify local economies, and empower women in particular, which can in turn contribute to adaptive capacity in a local context (Agrawala and Carraro, 2010; Moser et al., 2010). Micro-finance also provides a means for donors to deliver support to low-income groups without creating an ongoing dependence on aid. But there is a need to target it well to avoid encouraging growth in areas prone to climate risk (Hammill et al., 2008; Agrawala and Carraro, 2010). A limitation of micro-finance for adaptation is that it typically provides credit to individuals, so it is not easily used to finance collective investments—for instance, improving drainage—and it can be a route to indebtedness during disaster recovery. There has been some experience of pooling savings, for example, in low-income communities to set up City Development Funds in Asia, from which they can draw loans for disaster rehabilitation among other things (Archer, 2012). Von Ritter and Black-Layne (2013) explore the possible role for microfinance and crowd funding to support local climate change action e.g. finance small decentralized energy solutions or "climate-proof" homes; they also suggest the new Green Climate Fund could support such activity through its private sector window.

protect the poorest and most vulnerable households, and to ensure or enable action by the private sector. This may include filling gaps in insurance markets (Mills, 2007; Fankhauser et al., 2008; IPCC, 2012; UN-HABITAT, 2011c); helping provide information about risks particularly where this is highly uncertain; and encouraging pro-active engagement by the private sector, as in the UK where vulnerability assessment is required for infrastructure investments (Agrawala et al., 2011). There are examples of urban governments leading by example, requiring the integration of adaptation considerations into public operations and infrastructure investments through procurement requirements, which in turn affects private sector providers. Thus, even where markets exist and are well-functioning, all levels of government may need to engage the private sector in adaptation. Public-private initiatives also have a role providing educational and skill development resources to ensure that the professional networks of private service providers are trained in the latest decision tools, assessment methods, and practices (McBain et al., 2010; da Silva, 2012). Where markets do not exist or do not function well, there will be an even larger role for policy and public investments to support urban adaptation.

8.4.2.4. Philanthropic Engagement and Other Civil Society Partnerships

Philanthropic and other civil society support for urban adaptation is gaining momentum at all levels. The most diverse and numerous are local actions undertaken by community-based organizations, as described above. Philanthropic organizations demonstrate the enabling role that can be played by international civil society to support urban adaptation, particularly in cities and communities in low- and lower-middle-income countries. The coming together of grassroots civil society organizations to form international collaborations and networks can also strengthen the framing role of civil society while retaining local accountability and focus to support adaptation. Some examples include:

- Rockefeller Foundation's support for the Asian Cities Climate Change Resilience Network (ACCCRN) (Moench et al., 2011; Brown et al., 2012)
- The Asian Coalition for Community Action Program managed by the Asian Coalition for Housing Rights
- The Asian Disaster Reduction and Response Network (ADRRN)
- Philippines Homeless People's Federation, working with local governments to identify and help those most at risk to natural disasters (Carcellar et al., 2011)
- Shack/Slum Dwellers International (SDI), a network of community-based organizations and federations of the urban poor in 33 countries in Africa, Asia, and Latin America and their local support NGOs.

Many disaster events are small and local but, taken together, have a widespread and cumulative impact on the development prospects of low-income households and communities, underscoring the need for enhanced civil society engagement and coordination (UNISDR, 2009). Civil society organizations are well placed to address the local conditions and some of the structural root causes of vulnerability, necessary for successful urban adaptation. For example, the scale and range of recent disaster events in Asian cities suggest a growing need for new support

mechanisms to facilitate action among local stakeholders—one that should include local government as well as local civil society organizations (Shaw and Izumi, 2011). Where urban civil society is well coordinated and has legitimacy, it can offer alternative models for urban governance and adapting to climate change to assist local governments (Mitlin, 2012). Elsewhere ad hoc coalitions of civil society actors, or even uncoordinated activity in some cities, provide a de facto delivery mechanism for accessing basic infrastructure and rights as part of development and disaster response (Pelling, 2003), although the lack of coordination limits the scale and scope of adaptive capacity. Many civil society initiatives have developed models of infrastructure delivery that are not centered on urban adaptation but have relevance for it, in part through activities designed to reduce disaster risk and increase management capacity (see Hasan, 2006).

8.4.2.5. University Partnerships and Research Initiatives

Since AR4, interest in urban aspects of adaptation has grown in the research community and its funders, as is evident in the number of conferences on this topic, both within social and behavioral sciences and in engineering and city planning sciences. More professional societies are considering their roles and responsibilities. Some cities are tapping into relevant networks; for instance, the Urban Climate Change Research Network (UCCRN) brings together researchers and city planners to exchange knowledge and build a coalition of awareness and policy (Rosenzweig et al., 2010). Other examples include London's use of scenarios generated by UK Climate Impact Programme by University of Oxford's Environmental Change Institute (Carmin et al., 2013); the Urbanization and Global Environmental Change Programme (UGEC) of the International Human Dimensions Programme on Global Environmental Change; the Earth System Science Partnership (ESSP), a pioneer in promoting social science and knowledge exchange; the Land-Ocean Interactions in the Coastal Zone program; Integrated Research on Disaster Risk (IRDR) co-sponsored by the International Council for Science (ICSU), the International Social Science Council (ISSC), and the United Nations International Strategy for Disaster Reduction (UNISDR); and research on urban adaptation in Africa supported by the International Development Research Centre (IDRC).

Individual academic institutes have also begun to support urban adaptation efforts. The Urban Observatory in Manila has become a regional hub for climate change science and urban adaptation; the Universiti Kebangsaan in Malaysia hosts a Malaysian Network for Research on Climate, Environment and Development (MyCLIMATE) focused on awareness and capacity in industry and civil society (Shaw and Izumi, 2011); the Climate and Disaster Resilience Initiative (Kyoto University, CITYNET, and UNISDR) works with city managers and practitioners (Shaw and IEDM Team, 2009); and Latin American networks such as FLACSO (Facultad Latinoamericana de Ciencias Sociales) provide leadership across the region in disaster risk reduction, management, and climate change adaptation. Individual centers have also become more engaged in urban adaptation, for instance, UNAM (Universidad Nacional Autónoma de México) in Mexico and the International Centre for Climate Change and Development (ICCCAD) in Dhaka (Mehrotra et al., 2009; Anguelovski and Carmin, 2011). There remains a challenge to reform university curricula to include urban adaptation and mitigation.

8.4.2.6. City Networks and Urban Adaptation Learning Partnerships

Opportunities for accelerating learning and action may stem from horizontal coordination and networking across actors, professions, and institutions in different municipalities and metropolitan areas. The growing interest in urban adaptation is also seen in the growth of transnational networks and coalitions working across organizational boundaries to influence outcomes, both nationally and internationally (Bulkeley and Betsill, 2005; Bulkeley and Moser, 2007; Rosenzweig et al., 2010) and providing an institutional foundation to concerted effort and collaboration at the city level (Aall et al., 2007; Romero-Lankao, 2007; Kern and Gotelind, 2009). ICLEI's Cities for Climate Protection has been extensively analyzed in the literature (Betsill and Bulkeley, 2004; Lindseth, 2004; Betsill and Bulkeley, 2006; Aall et al., 2007) with a broad conclusion that they are influencing decision making and offer an effective means of sharing experience and learning. Other examples include the Climate Alliance, the C-40 Large Cities Climate Leadership Group, and the Urban Leaders Adaptation Initiative in the USA (OECD, 2010). The United Cities and Local Governments (UCLG) network, representing local governments within the United Nations, also has a growing interest in adaptation. The Asian Cities Climate Change Resilience Network, mentioned above, also encourages inter-city learning for officials and local researchers (Brown et al., 2012). The Making Cities Resilient network, supported by the UN International Strategy for Disaster Risk Reduction (UNISDR), promotes a 10-point priority agenda for city governments, building on good risk reduction practices (UNISDR, 2008; see also Johnson and Blackburn, 2013). Another example of the influence of city networks is the signing of the Durban Adaptation Charter in December 2011 by 107 mayors representing more than 950 local governments at COP17 (Roberts and O'Donoghue, 2013), signaling their intention to begin addressing climate change adaptation in a more concerted and structured way (Rosenzweig et al., 2010). The initial focus of some city networks was on mitigation but attention and leadership on adaptation is growing (as in the U.S. Urban Leaders Adaptation Initiative; Foster et al., 2011a).

8.4.3. Resources for Urban Adaptation and Their Management

Resources for urban adaptation action can come from public and private sectors, domestic and international. Table 8-5 summarizes the main funding sources and financial instruments. In high-income countries, local governments are responsible for an estimated 70% of public spending in urban areas and roughly 50% of public spending on environment infrastructure, often in partnership with other levels of government (OECD, 2010). The scale and source of funds contributing to adaptation varies widely by location and depends in part on the extent to which local authorities can tax residents, property owners, and businesses. A survey of 468 cities conducted by Carmin et al. (2012a) found that most (60%) are not receiving any financial support for their adaptation actions. Of the small percentage of cities receiving funding, the most common source of support is from national governments (24%). A smaller number of cities (9%) reported funding from subnational governments while others (8%) reported support from private foundations and non-profit organizations; only 2 to 4% of the cities reported receiving

financial support from international (bilateral and multilateral) financial institutions such as multilateral development banks and this varied widely by region (Carmin et al., 2012a). Some of the environmental innovation in Latin America over the last 20 years is associated with decentralization that has strengthened fiscal bases for cities, along with more elected mayors and more accountable city governments (Campbell, 2003; Cabannes, 2004); Latin American cities have also reported multilateral development banks as the most prevalent source of funding for adaptation representing about 21% of funding to date (Carmin et al., 2012a). In Africa and Asia, a high proportion of urban governments still have very limited investment capacities, as most of their revenues go to salaries and other recurrent expenditures (UCLG, 2011). UCLG data points to the large difference in annual expenditure per person by local governments, ranging from more than US$6000 in some high-income nations to less than US$20 in most low-income nations (UCLG, 2010).

As Table 8-5 indicates, large cities with strong economies and administrative capacity can best attract external funding (including transfers from higher levels of government) and raise internal funding for adaptation. Less prosperous and smaller urban centers and cities with fragmented governance structures or administrations lacking in capability have worse prospects. A key issue is "unfunded mandates"—responsibilities assigned to cities with no increase in funding and capacity (UCLG, 2011)—and this can happen with new responsibilities around climate change (Kehew et al., 2012; Tavares and Santos, 2013). Funding regimes and supportive legal frameworks need to integrate urban climate change risk management and adaptation into development.

8.4.3.1. Domestic Financing: Tapping into National or Subnational Regional Sources of Funding and Support

For adaptation specifically, domestic public funding is one of the most significant and sustainable sources in many countries. Initiatives to green local fiscal policies are spreading, including congestion charges on motor vehicles and value-capture land taxes that make the cost of environmental externalities visible, and/or the benefits of infrastructure and services to property owners (e.g., transport, water, and wastewater services). Such measures can promote private investment in risk management while mobilizing local revenue sources. Local fiscal incentives can lead to maladaptation where urban government budgets and actions are financed by land sales, which in turn promote urban sprawl or development in areas at risk (Drejza et al., 2011; Merk et al., 2012). Greening local fiscal policies will need to identify and address these kinds of concerns.

Grants, loans, and other revenue transfers from national or regional (subnational) governments are also important sources, for instance to compensate local governments for the spillover environmental benefits of their expenditures (OECD, 2010; Hedger, 2011; Hedger and Bird, 2011). An example is municipal funding in Brazil, where the allocation of tax revenues is based on ecosystem management performance (Box 8-3).

Other innovative financial mechanisms for urban adaptation include revolving funds and the energy services company ("ESCO") model (OECD, 2010). Revolving funds can be developed from a variety of revenue streams such as Clean Development Mechanism projects (Puppim de Oliveira, 2009), and savings from energy efficiency investments in

Table 8-5 | Main sources of funding and financial instruments for urban adaptation.

Sources of funding	Types	Instruments	What can be funded (with some examples of funds)	Urban capacity required to access funding
Local: public	Local revenue raising policies: taxes, fees, and charges or use of local bond markets	• Local taxes (e.g., on property, land value capture, sales, businesses, personal income, vehicles…) • User charges (e.g., for water, sewers, public transport, refuse collection) • Other charges or fees (e.g., parking, licenses)	• Urban infrastructure and services • Urban adaptation programs and planning processes • Urban capacity building	Cities with well-functioning administrative and institutional capacity and adequate funding from local revenue generation and intergovernmental transfers
Local: public-private	Public-Private Partnerships (PPP) contracts and concessions	• Concessions and private finance initiatives to build, operate, and/or maintain key infrastructure • Energy performance contracting	Medium to large-scale infrastructure with strong private goods (to allow rents for private sector)	Cities with strong capacity for legal oversight and management
Local or national: private or public	National or local financial markets	• Commercial loans • Private bonds • Municipal bonds	Basic physical infrastructure (need for collateral)	Well-functioning local or national financial markets that city governments can access
National: public	National (or state/provincial) revenue transfers or incentive mechanisms	• Revenue transfers from central or regional government • Payment for ecosystem services or other incentive measures	• Urban payment for environmental services in Brazil • Sweden's KLIMP climate investment program	Cities with good relations with national governments, strong administrative capacity to design and implement policies and plans
International: private	Market-based investment	• Foreign direct investment, joint ventures	• Industrial infrastructure • Power generation infrastructure	Cities with strong national enabling conditions and policies for investment
International sources	Grants, concessional financing (e.g., Adaptation Fund)	• Grants, concessional loans, and loan guarantees through bilateral and multilateral development assistance • Philanthropic grants	• Urban capacity building • Urban infrastructure adaptation planning	Typically requires strong multi-level governance—cities with good relations with national governments. Cities with low levels of administrative and financial market capacity.

Box 8-4 | Environmental Indicators in Allocating Tax Shares to Local Governments in Brazil

In Brazil, part of the revenues from a value-added state government tax (ICMS) must be redistributed among municipalities. Three-quarters is defined by the federal constitution with the remaining 25% allocated by each state government. The state of Paraná introduced the ecological ICMS (ICMS-E) in 1992 against the background of state-induced land use restrictions (protected areas) for several municipalities, which prevented them from developing land but provided no compensation. For example, 90% of the Piraquara municipality was designated as a protected watershed, supplying the Curitiba metropolitan region with water (May et al., 2002).

States have different systems in place, but there are many commonalities. Revenues are allocated based on the proportion of a municipality's area set aside for protection, and protected areas are weighted according to different categories of conservation management (higher for biological reserves, for instance, than for areas of tourist interest). Paraná and some other states evaluate the protected areas based on physical and biological quality (fauna and flora); quality of water resources; physical representativeness; and quality of planning, implementation, and maintenance.

The ICMS-E, built on existing institutions and administrative procedures, has had very low transaction costs (Ring, 2008). Evaluations show it has been associated with improved environmental management and the creation of new protected areas (May et al., 2002). It has also improved relations with the surrounding inhabitants as they start to see these areas as an opportunity to generate revenue, rather than an obstacle to development.

Adapted from OECD, 2010.

municipal buildings to feed public funds for investments that yield adaptation benefits. Local governments in high- and some middle-income countries may also have direct access to bond markets or loans from national (or regional) development banks or financial institutions (OECD, 2010; Merk et al., 2012). Local access to capital markets can be facilitated through risk-sharing mechanisms or guarantees provided by development banks, for example, the German government's Development Bank KfW provides low-interest loans to local banks which then finance energy-efficient renovations in residential and commercial buildings (OECD, 2010; Pfliegner et al., 2012).

A key challenge is determining how far adaptation funding should be geared to target associated policy realms. The very high costs of extreme weather events in many urban areas, and the fact that climate change usually increases these risks, indicates the need for increased funding and attention from national budgets for risk reduction and early warning and evacuation procedures within urban areas, alongside other adaptation measures (World Bank, 2010a,e; Hallegatte and Corfee-Morlot, 2011). The urban funding gap may be particularly wide for "soft" rather than "hard" infrastructure investments, yet both can be a motor for resilience.

8.4.3.2. Multilateral Humanitarian and Disaster Management Assistance

The international humanitarian community is increasingly active in urban contexts, with relevance for adaptation capacity (IFRC, 2010). Non-climate-related disasters (including earthquakes and tsunamis) provide a learning opportunity, and the sector is beginning to review experience and develop appropriate tools and guidelines for urban contexts (e.g., ALNAP, 2012). In 2009, humanitarian groups formed a reference group on meeting humanitarian challenges in urban areas, setting a 2-year action plan in 2010, and developing a database of urban-specific aid tools, the Urban Humanitarian Response Portal (http://www.urban-response.org/). Policies sensitive to the needs of internally displaced urban populations are a big challenge for the sector, especially where the resident population is chronically poor (Crawford et al., 2010; Zetter and Deikun, 2010); so too are appropriate responses to increased urban food insecurity (Battersby, 2013).

The systematic programming of climate change adaptation into multilateral humanitarian, disaster response, and management funding within development cooperation is in its infancy. Urban dimensions are under-developed although this is changing (UNISDR, 2009, 2011; IFRC, 2010). The World Bank's Global Facility for Disaster Reduction and Recovery (GFDRR) explicitly includes adaptation to climate change. Its Country Programmes for Disaster Risk Management and Climate Change Adaptation 2009–2011, and more recently 2014–2016, seek to deepen engagement in some priority countries (GFDRR, 2009, 2013; World Bank, 2013). The GFDRR, with UNISDR, has also advocated for more integrated policy and advisory services at the technical level (see Mitchell et al., 2010). A 2009–2011 survey of reports from 82 governments on disaster risk reduction and urban and climate change issues found some progress in both areas (Figure 8-6; UNISDR, 2011).

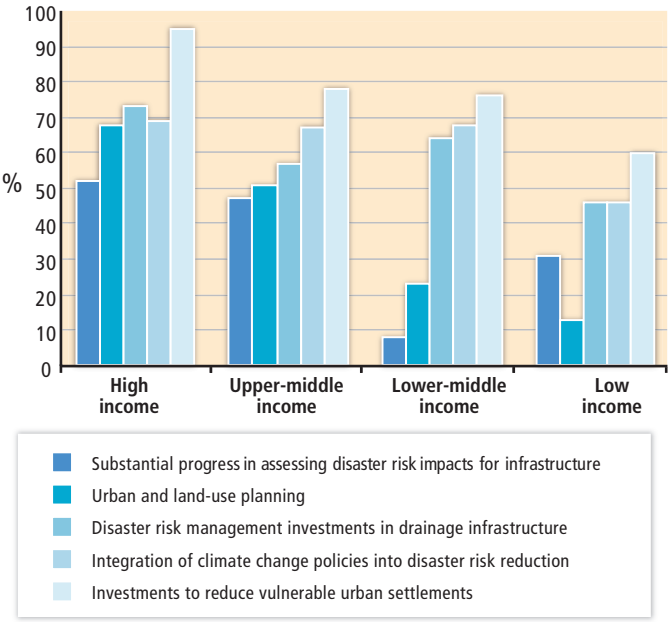


Figure 8-6 | Progress reported by 82 governments in addressing some key aspects of disaster risk reduction by countries' average per capita income (UNISDR, 2011).

Despite progress, many urban governments lack the capacity to address disaster risk reduction and management. Almost 60% of the countries surveyed by the UN (80% of lower-middle-income countries) reported that local governments have legal responsibility for disaster risk management, but only about a third had dedicated budget allocations, mostly in upper-middle- and high-income countries (UNISDR, 2011). Figure 8-6 highlights attention to investments in drainage infrastructure, but much less in urban and land use planning in lower-middle- and low-income countries. Progress in integrating climate change policies into disaster risk reduction was reported by more than two-thirds of governments in high-, upper-middle-, and lower-middle-income countries but under half of low-income countries.

8.4.3.3. International Financing and Donor Assistance for Urban Adaptation

The limited data available show attention to urban areas in the growing levels of international development financing available to support adaptation (e.g., OECD, 2013; World Bank, 2013). Development finance is a key source of support for adaptation in many low- and middle-income countries, but many vulnerable cities and municipalities are poorly positioned to access available funding (ICLEI, 2010; Paulais and Pigey, 2010), for their often very large deficits in risk-reducing infrastructure and services. In some local governments, international programs offer the main source of institutional and financial support for mitigation and adaptation work at the local level, but this can raise the danger of a "donor-driven model" (where the funding agency's agenda does not coincide with local priorities); experience shows that without strong and lasting local ownership, programs are unsustainable once support is withdrawn (Hedger, 2011; OECD, 2012). More international funding for adaptation and mitigation is being committed, largely as Official Development Assistance (ODA), and governments are broadly on track delivering on their international promises (see, e.g., the Cancun Agreements) to scale up international climate finance (Buchner et al., 2012; Clapp et al., 2012). Less in evidence are sound institutional arrangements to make this support available to urban governments. The *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) calls for arrangements that will allow adaptive urban management systems to evolve with changing social and environmental dynamics (IPCC, 2012) but international channels for development finance have yet to adjust to this call to action.

Recent data suggest that a small share of total flows of climate-related ODA targets adaptation (UNEP, 2011; OECD, 2012), and some of this is supporting urban adaptation (e.g., see OECD, 2013; World Bank, 2013). OECD estimates bilateral ODA commitments targeting climate change to be in the range of US$11 to US$20 billion per year on average in 2010–2011 for both adaptation and mitigation; of this, roughly 20 to 40% targets adaptation (OECD, 2013). One in-depth assessment of five major donors, covering concessional and non-concessional finance, estimated adaptation to be 30% of their climate change portfolio, mostly targeted to water and sanitation (about 75%) (UNEP, 2011). The rest were for other relevant sectors (i.e., transport, policy loans, disaster risk reduction), but with energy and health largely overlooked (UNEP, 2011; see also Atteridge et al., 2009). Despite growing attention to climate change, many bilateral agencies have historically had very limited engagement with urban initiatives (Mitlin and Satterthwaite, 2013). Some authors also note the difficulty in distinguishing adaptation from development finance, which limits the accuracy of such estimates (Tirpak et al., 2010; Buchner et al., 2012).

Despite the uncertainties in tracking adaptation ODA, OECD statistics (OECD, 2013) show that there is some attention to urban issues today.[2] Urban adaptation is estimated to represent about 20% of bilateral climate adaptation portfolios, equivalent to US$0.65 to US$1.6 billion per year (on average over 2010–2011). Slightly more than half of this goes to projects in urban centers with between 10,000 and 500,000 inhabitants while the rest goes to large cities with 500,000 or more inhabitants. The major sectors are water (about 38%, considering projects that had adaptation as principal or significant) and sanitation (another 6%) (OECD, 2013). The largest providers of urban adaptation ODA in these years were Japan (an average of US$683 million a year in commitments), Germany (US$333 million); France (US$111 million); and South Korea, European Union Institutions, Spain, and Denmark (between US$48 and US$80 million). The largest recipients were Vietnam (US$232

[2] Data and information as found in the OECD DAC-CRS 2013, www.oecd.org/dac/stats/rioconventions.htm (last accessed: September 7, 2013). These estimates derive from data and project descriptions in the OECD DAC-Creditor Reporting System. It is based on a project-by-project review of qualitative information in the 2013 version of the database describing official development finance from bilateral agencies and the EU institutions. This subset of "urban" adaptation activities describes those projects that identify the geography of beneficiaries as urban and that include a verifiable location (e.g., metropolitan Lima); data were organized by key characteristic of each urban location (i.e., population size and recipient country). Only urban areas with populations of 10,000 or more are included here. Projects are marked with climate adaptation "Rio marker"; this data set includes all projects marked as targeting climate adaptation, either as a principal objective or as those with it as a significant objective.

million); Bangladesh (US$146 million); China (US$100 million); and the Philippines, Peru, Indonesia, and Kenya (US$52 to US$76 million).

Around 70% of urban adaptation aid is dedicated to "hard" infrastructure while about 10% goes to "soft" measures to support capacity building related to urban infrastructure planning and adaptation. So OECD data suggest that urban adaptation is a recent but significant objective in climate aid activities but it is still only a small part of overall ODA portfolios (OECD, 2013).

Conventional channels for development finance appear to have the biggest role in adaptation financing in low- and middle-income countries, though new vertical funds are also emerging. The proliferation of multiple, single purpose funding mechanisms runs contrary to long-standing harmonization principles of sound development cooperation (Hedger, 2011; OECD, 2012). This more complex funding architecture makes it difficult for smaller actors such as local authorities to access sources for timely adaptation investments.

Development assistance can be better targeted if reconciled with bottom-up, locally based planning processes that take climate risks into account, and programs aiming to be mainstreamed into urban development over time (Brugmann, 2012). Research shows the lack of well-defined priorities in partner countries, combined with a donor tendency to "control" funds for short-term results and a large variety of different funding instruments results in fragmented delivery systems and unclear outcomes (Brown and Peskett, 2011). Even where climate strategies exist to guide action—as in Bangladesh, an "early mover" on adaptation planning—the plan is often neither costed nor sequenced, making it an inadequate framework for finance delivery (Hedger, 2011). A key to improving effectiveness of international public finance will be building the capacity for country-led planning processes identifying priority actions for targeting adaptation funds. National Adaptation Plans of Action (NAPAs) have become a principal way of organizing adaptation priorities in Least Developed Countries, but the majority of plans do not explicitly include urban projects and do not reflect local government perspectives (UN-HABITAT, 2011c).

A number of authors conclude that international development finance is failing to tackle urban adaptation financing needs (Parry et al., 2009; Paulais and Pigey, 2010; ICLEI, 2011; UN-HABITAT, 2011c). Some suggest that national governments could set up funds supported by international finance (governmental, philanthropic, or both) and on which urban governments and community-based organizations can draw (Paulais and Pigey, 2010; Satterthwaite and Mitlin, 2014). In some middle-income countries, such as Indonesia, a more effective and sustainable strategy than a focus on external funding may be national policy reforms and incentives to steer investment to priority needs (Brown and Peskett, 2011). There is also a need to mobilize domestic public and private investment to ensure delivery of adaptation at national and urban levels (Hedger, 2011; Hedger and Bird, 2011; OECD, 2012). Accessing all these sources of development finance for urban adaptation will require institutional mechanisms to support multi-level planning and risk governance (Corfee-Morlot et al., 2011; Carmin et al., 2013).

8.4.3.4. Institutional Capacity and Leadership, Staffing, and Skill Development

Leadership is critical for generating interest in urban adaptation and championing awareness and institutional change to bring action (Anguelovski and Carmin, 2011; Carmin et al., 2012a). Creating a climate change and environmental focal point or office in a city can help coordinate climate action across government departments or agencies (Roberts, 2008, 2010; Anguelovski and Carmin, 2011; Hunt and Watkiss, 2011; OECD, 2011; Brown et al., 2012). Yet there may be downsides when this function is housed in the environmental line department—see Durban (Roberts, 2008), Boston (City of Boston, 2011), and Sydney (Measham et al., 2011)—since they are typically among the weakest parts of city government with limited influence (Roberts, 2010).

Although there is growing evidence of urban adaptation leadership (Lowe et al., 2009; Anguelovski and Carmin, 2011; Foster et al., 2011b), there are also important political constraints at the local level. Powerful

Box 8-5 | Adaptation Monitoring: Experience from New York City

The adaptation monitoring approach developed for New York City has four indicator elements: (1) physical climate change variables; (2) risk exposure, vulnerability, and impacts; (3) adaptation measures; and (4) new research in each of these categories. Examples of indicators arising from these categories include the percentage of building permits issued in a given year in current Federal Emergency Management Agency (FEMA) coastal flood zones, and in projected 2080 coastal flood zones; a tally of building permits with measures to reduce precipitation runoff; an index based on insurance data that measures the insurer's perception of the city's infrastructure-coping capacity; an index that measures the rating of city-issued bonds or infrastructure operators for capital projects with climate change risk exposure; the detailed trend of weather-related emergency/disaster losses (whether insured or uninsured, relative to the total asset volume); and the number of days with major telecommunication outages (wireless versus wired), correlated with weather-related power outages. Data criteria were decided through a scientist-stakeholder consensus with designated groups to evaluate prospective indicators and their values. This case study shows the need for interdisciplinary, longitudinal data collection and analysis systems along with an inclusive, transparent process for stakeholder engagement to interpret the data (Jacob et al., 2010).

vested interests may oppose attention to adaptation and promote development on sites at risk. As noted earlier, concerns about employment and competitiveness make it difficult for local governments to focus on the more distant implications of climate change. This is especially so during periods of economic hardship (Shaw and Theobald, 2011; Solecki, 2012). A key step forward is institutionalizing different types of behavior and norms.

Beyond goal setting and planning, the literature also suggests the need for regulatory frameworks to require relevant behavior and investment. Governments can institute small changes, such as job descriptions that require actions and provide incentives to act in new ways (e.g., for line managers and sector policy makers) or by providing training and clear guidance to staff (Moser, 2006; Carmin et al., 2013; Tavares and Santos, 2013). Budgetary transparency and metrics to measure progress on adaptation can also help to institutionalize changes in planning and policy practice (OECD, 2012).

8.4.3.5. Monitoring and Evaluation to Assess Progress

Adaptation leaders and funding institutions need tools for monitoring and evaluating urban adaptation actions to justify investments but these are not well developed yet or widely implemented in urban areas (Kazmierczak and Carter, 2010). This requires indicators that show if adaptation is taking place, at what pace, and in what locations. Relevant evaluation criteria include cost, feasibility, efficacy, co-benefits (direct and indirect), and institutional considerations (Jacob et al., 2010). Assessment methods can capture outcomes of adaptation decisions, or the decision-making processes themselves—ideally both. Monitoring is challenging for adaptation, especially urban, given the lack of standard metrics, the differences in local contexts, and the often localized nature of adaptation (Lamhauge et al., 2012; Spearman and McGray, 2012).

City authorities, NGOs, and researchers have begun to design adaptation monitoring and evaluation frameworks. Box 8-5 presents the experience of New York City. Development of standard tools offers scope for international benchmarking and coordination across scales of assessment, for example, by associating local indicators of resilience with those in the Hyogo Framework for Action (that prioritize disaster risk reduction) and the post-2015 development agenda (IFRC, 2011).

Monitoring and evaluation focusing on the effectiveness of donor aid on climate adaptation is a growing area of research (Chaum et al., 2011; Lamhauge et al., 2012; Spearman and McGray, 2012). Recent work shows the urgent need for consistent and internationally harmonized data collection to support monitoring. This is a concern for both adaptation and wider disaster risk reduction spending, suggesting a systemic challenge to the architecture of international finance (Kellett and Sparks, 2012). Steps are being made through multi-site assessment programs, in some instances including treatment of urban issues. For example, the World Bank recently included an adaptive capacity index as part of an analysis of risk and adaptation options for five cities in Latin America and the Caribbean. The methodology was previously applied in Guyana, where it demonstrated a gap between national and city level adaptive capacity (Pelling and Zaidi, 2013).

Monitoring also needs to consider the delivery and use in cities of international climate finance to ensure that funds are being effectively directed (Chaum et al., 2011; Hedger, 2011). This is especially important for cities at an early stage of planning, implementing, and monitoring of adaptation, as they can learn from one another's experiences. There is some evidence that international agencies overburden partner organizations and countries (including in some cases city authorities) with monitoring requirements; with limited local capacities, this can detract from further program design and implementation.

8.5. Annex: Climate Risks for Dar es Salaam, Durban, London, and New York City

Refer to Table 8-6 for four city profiles of current and indicative future climate risks, covering Dar es Salaam, Durban, London, and New York. Each summarizes the present, near-term (2030–2040), and long-term (2080–2100) climate risks and the potential for risk reduction through adaptation. As noted earlier, data should not be compared between cities but trends in adaptive capacity and impact can be drawn out.

References

Aall, C., K. Groven, and G. Lindseth, 2007: The scope of action for local climate policy: the case of Norway. *Global Environmental Politics*, **7(2)**, 83-101.

Adamo, S.B., 2010: Environmental migration and cities in the context of global environmental change. *Current Opinion in Environmental Sustainability*, **2(3)**, 161-165.

Adelekan, I.O., 2010: Vulnerability of poor urban coastal communities to flooding in Lagos, Nigeria. *Environment and Urbanization*, **22(2)**, 433-450.

Adelekan, I.O., 2012: Vulnerability to wind hazards in the traditional city of Ibadan, Nigeria. *Environment and Urbanization*, **24(2)**, 597-617.

Adger, N., I. Lorenzoni, and K. O'Brien, 2009: Adaptation now. In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, N., I. Lorenzoni, and K. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK, pp. 1-22.

AGF, 2010a: *Report of the Secretary-General's High-level Advisory Group on Climate Change Financing.* United Nations Advisory Group on Climate Change Financing (AGF), United Nations, New York, NY, USA, 61 pp.

AGF, 2010b: *Work Stream 7: Public Interventions to Stimulate Private Investment in Adaptation and Mitigation*. United Nations Advisory Group on Climate Change Financing (AGF), United Nations, New York, NY, USA, 35 pp.

AGF, 2010c: *Work Stream 4: Contributions from International Financial Institutions*. United Nations Advisory Group on Climate Change Financing (AGF), United Nations, New York, NY, USA, 35 pp.

Agrawala, S. and M. Carraro, 2010: *Assessing the Role of Microfinance in Fostering Adaptation to Climate Change.* OECD Environment Working Paper No. 15, Organisation for Economic Co-operation and Development (OECD), OECD Publishing, Paris, France, 37 pp.

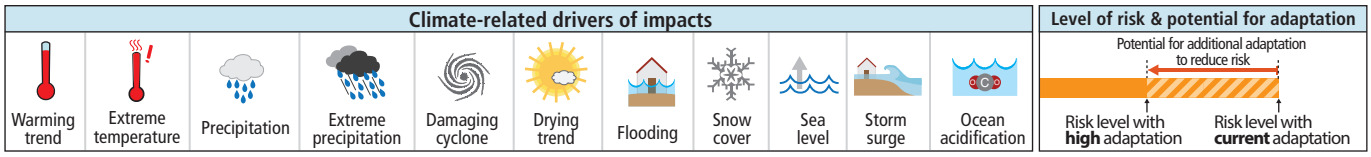
Agrawala, S., M. Carraro, N. Kingsmill, E. Lanzi, M. Mullan, and G. Prudent-Richard, 2011: P*rivate Sector Engagement in Adaptation to Climate Change: Approaches to Managing Climate Risks*. OECD Environment Working Paper No. 39, Organisation for Economic Co-operation and Development (OECD), OECD Publishing, Paris, France, 55 pp.

Agrawala, S. and S. Fankhauser (eds.), 2008: *Economic Aspects of Adaptation to Climate Change: Costs, Benefits and Policy Instruments.* Organisation for Economic Co-operation and Development (OECD), OECD Publishing, Paris, France, 133 pp.

Agrawala, S. and M. van Aalst, 2008: Adapting development cooperation to adapt to climate change. *Climate Policy*, **8(2)**, 183-193.

Ahmed, A.U., R.V. Hill, L.C. Smith, D.M. Wiesmann, and T. Frankenberger, 2007: *The World's Most Deprived: Characteristics and Causes of Extreme Poverty and Hunger*. International Food Policy Research Institute (IFPRI), Washington, DC, USA, 145 pp.

Table 8-6 | Current and indicative future climate risks for Dar es Salaam, Durban, London, and New York City.



Dar es Salaam

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Coastal zone systems (*medium confidence*) [8.3.3.3, 8.3.3.4]	Construction of coastal protection structures such as sea walls and groynes to minimize coastal erosion and land inundation in Dar es Salaam. Medium prospects due to high costs.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C / 4°C	Very low – Medium – Very high
Terrestrial ecosystems and ecological infrastructure (*low confidence*) [8.3.3.7, Table 8-2]	Demarcation and protection of green areas, provision of more drainage systems, and protection of urban wetlands and ground water resources. Low prospects due to poor development control including land use management.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C / 4°C	Very low – Medium – Very high
Water supply systems (*high confidence*) [8.2.4.1, 8.3.3.4, Table 8-2]	Improvement in Dar es Salaam's water resources management and increased coverage and efficiency in water supply systems. Medium prospects as some of these measures are already being implemented.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C / 4°C	Very low – Medium – Very high
Waste water system (*high confidence*) [8.2.4.1, 8.3.3.4, Table 8.2]	Increase in spatial coverage of sewerage and improvement of on-site excreta disposal systems. Low prospects for extending sewer coverage; higher prospects for expanding onsite disposal systems.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C / 4°C	Very low – Medium – Very high
Energy systems (*very high confidence*) [8.2.4.2]	Reduced dependence on hydropower as the main source of energy by replacing it with natural gas. Very high prospects as the country has vast resources of natural gas.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C / 4°C	Very low – Medium – Very high
Food systems and security (*high confidence*) [8.3.3.2]	Urban and peri-urban agriculture and new adaptation policies to take into account impacts of climate change on food costs and supply chain. Enhanced social safety nets can support adaptation measures.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C / 4°C	Very low – Medium – Very high
Transportation and communication systems (*medium confidence*) [8.2.4.3, 8.3.3.6]	New design standards in context of climate change and enforcement of development controls. Low prospects as climate change issues are yet to be mainstreamed in the sector.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C / 4°C	Very low – Medium – Very high

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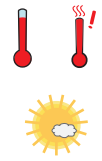
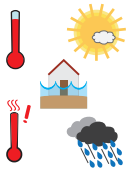
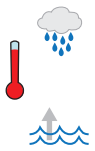
Table 8-6 (continued)

Dar es Salaam (continued)

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Housing (*high confidence*) [8.2.4.4,8.3.3.3]	Climate change adaptation plans, new building codes, effective development control, and upgrading of informal settlements. High prospects as some of these measures are already being taken into account.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Human health (*medium confidence*) [8.3.3]	Improvement of water supply, solid waste management, housing conditions, land use planning and food security, and provision of health insurance. Medium prospects as these are key development issues that require a lot of financial resources.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Key economic sectors and services (*medium confidence*) [8.3.3.1]	Improvement of storm water infrastructure and transport networks. Use of natural gas as main source for power generation, relocating of key economic activities and infrastructure along coastal buffer areas. A mixture of high and low prospects due to availability of natural gas and high requirements of financial resources.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Poverty and access to basic services (*high confidence*) [8.3.3]	Formalizing informal economic sector, upgrading of informal settlements, improvement of housing conditions and empowering local communities in tackling problems related to climate change. High prospects as this is already being implemented as a development issue.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high

Durban

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Coastal zone systems (*medium confidence*) [8.3.3.3]	Maintaining and restoring Durban's coastal ecosystems. Use of coastal protection structures such as geofabric sand bags, retaining walls, groynes, and a beach nourishment scheme to minimize coastal erosion and infrastructure damage. Use of a development setback line and in some instances strategic retreat to protect infrastructure. High prospects as systems for coastal protection exist and are being improved, but may be overwhelmed by the increase in severity and frequency of storm surges over time.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Terrestrial ecosystems and ecological infrastructure (*medium confidence*) [8.3.3.4]	Design and implementation of a fine-scale systematic conservation plan to protect a representative and persistent system of local biodiversity and related ecosystem services. Remove non-climate threats e.g., by managing alien invasive species. Medium prospects due to lack of human and financial resources to protect and manage system and poor enforcement of contraventions.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Water supply systems (*high confidence*) [8.3.3.4]	Demand and supply side management required. Reduce non-revenue water losses. Use of ecological infrastructure to improve level of assurance. Medium prospects as measures are already being implemented or considered.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Waste water system (*high confidence*) [8.3.3.4]	Increase in spatial coverage of Durban's waterborne sewerage system and use of appropriate alternative services in areas too costly to serve with waterborne systems. Recycling of waste water to potable standards. Medium prospects as measures are already being implemented or investigated.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high

Continued next page →

Table 8-6 (continued)

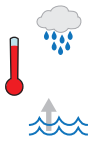
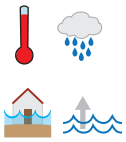
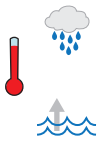
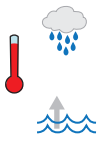
Durban (continued)				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Energy systems (*medium confidence*) [8.3.3.5]	No integration of energy policy with adaptation policy or practice. Need to avoid maladaptation e.g., increased electricity use for cooling in response to rising temperatures. Low prospects as institutional structures not yet in place to drive this integration.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Food systems and security (*high confidence*) [8.3.3.2]	Need to change planting dates and to provide increased crop irrigation. Need to take into account the impacts of climate change on the full food supply chain. Low prospects as climate change not yet considered a serious threat.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Transportation and communications systems (*medium confidence*) [8.3.3.6]	New design standards in context of climate change and enforcement of development control. Medium prospects as climate change issues are beginning to be considered in the transportation sector.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Housing (*high confidence*) [8.3.3.3]	New building codes, effective development control, upgrading of informal settlements, and retrofitting of existing housing stock. Changes in stormwater policy, preparation of master drainage plans, use of attenuation facilities, and calculation of new floodlines. Promotion of higher densities to reduce pressure on ecological infrastructure. Medium prospects as measures are already being implemented or being investigated.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Human health (*high confidence*) [8.3.3]	Improvement of basic services, housing conditions, land use planning, and food security. Extend coverage of primary health care and health insurance. Maintain and extend vector control. Ensure ability to deal with the impacts of large-scale disasters through inter-sectoral coordination. Low to medium prospects due to limited human and financial resources.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Key economic sectors and services (*medium confidence*) [8.3.3.1]	Durban is a logistics, manufacturing, and tourist center. Need to protect and properly locate vulnerable infrastructure in coastal areas, particularly port-related infrastructure. High prospects because of the national economic significance of the port and petro-chemical sectors and local economic significance of tourism.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Poverty and access to basic services (*high confidence*) [Box 8-2, 8.3.3.7]	Formalizing informal economic sector, upgrading informal settlements, provision of interim services to informal settlements, improving housing conditions, and increasing the adaptive capacity of local communities (especially through ecosystem based adaptation). Use of climate change adaptation interventions to create employment opportunities. Medium prospects because of the scale of the problem and related costs.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
London				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
River/coastal zone systems (*high confidence*) [8.3.3.4]	London is currently well protected from tidal flooding and has utilized an "adaptation pathways" approach to ensure it identifies and delivers a flexible long-term tidal flood risk management plan to maintain a high standard of protection through the century.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high

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Table 8-6 (continued)

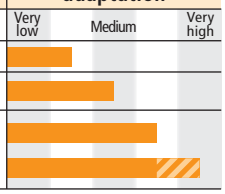
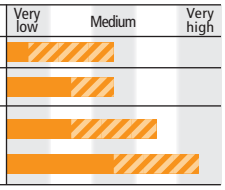
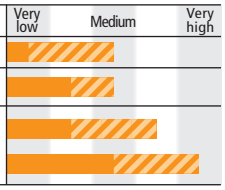
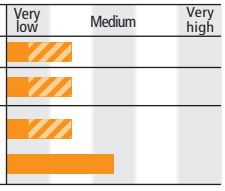
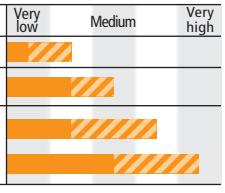
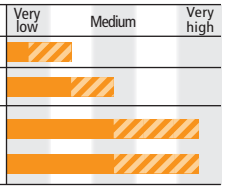
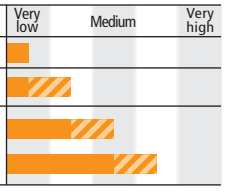
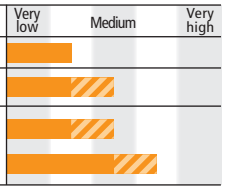
London (continued)				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Terrestrial ecosystems and ecological infrastructure (*medium confidence*) [8.3.3.7]	Adaptation is compromised primarily by habitat fragmentation and can be exacerbated, especially in wetland habitats, by invasive species. The city is taking an approach that promotes the multifunctional benefits of ecologically designed urban green spaces to benefit adaptation with restoring ecological function.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Water supply systems (*high confidence*) [8.3.3.4]	London faces increasing water security issues during droughts created by higher relative per capita consumption, aging infrastructure, a rapidly growing population, and projected diminishing resources. Resilience is being increased through programs to reduce consumption and increase the diversity of supply.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Waste water system (*high confidence*) [8.3.3.4]	Much of London is served by a combined rain and foul water drainage system that regularly overflows into the River Thames. Population growth, urban creep, and projected more intense rainfall will further challenge the system. The city is working with the relevant drainage partners to manage this increasing risk through a combination of gray and green infrastructure.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Energy systems (*medium confidence*) [8.3.3.5	The city's energy security is threatened by a reduction in national generation capacity and the resilience of local distribution systems not matching the increasing demand. The city is responding through increasing energy efficiency and local energy production to improve resilience. Some concern over amplifications effects of energy system failure during heat or cold shocks.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Food systems and security (*low confidence*) [8.3.3.2]	London's food supply is globalized and access is strongly influenced by global food prices relative to income, as well as regional and national agricultural productivity.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Transportation and communication systems (*medium confidence*) [8.3.3.6]	London is served by a complex communications and public transport network, which though vulnerable in parts has sufficient redundancy to be resilient at the strategic level. Detailed risk assessments are informing an investment program in the transport network that will deliver increasing resilience to climate impacts.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Housing (*high confidence*) [8.3.3.3]	London has an extensive historic housing stock that demonstrates poor thermal performance in summer and winter and poor water efficiency. A significant proportion of this housing stock is at risk of flooding. There is improving integration between mitigation and adaptation policy implementation at the regional level, but insufficient funding and levers to implement widespread adaptation.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Human health (*high confidence*) [8.2.2.1, 8.2.3.1]	Health observation systems and care delivered through the National Health Service respond well but need to integrate better with social care provision to be more proactive, especially for vulnerable groups such as the elderly.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	

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Table 8-6 (continued)

London (continued)

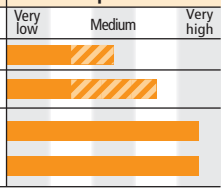
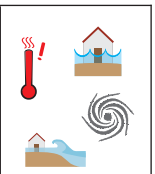
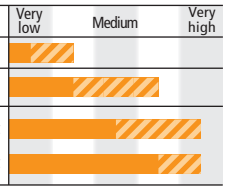
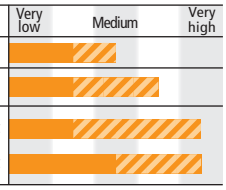
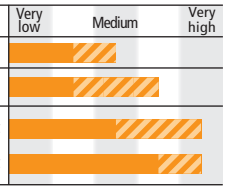
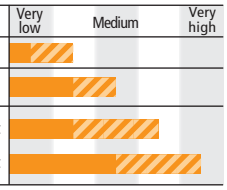
Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Key economic sectors and services (*medium confidence*) [8.3.3.1]	London's economy is dominated by service sector activities, particularly finance and including global businesses that expose it to failure in external markets that may be associated with climate change impacts or management. Business continuity is routinely integrated into business plans. Failure of essential infrastructure, including transport and energy networks, has short-term impacts.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
Poverty and access to basic services (*high confidence*) [8.3.3.8]	A significant proportion of the population struggles to pay their energy and water bills. Pockets of deprivation create areas of high vulnerability to climate risks, compounded by low levels of community capacity / social networks.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high

New York City

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Coastal zone systems (*very high confidence*) [8.2]	NYC is highly vulnerable to coastal storm events and sea level rise associated flooding. Integration of infrastructure and policy changes with opportunity to enhance ecosystem service services is possible.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
Terrestrial ecosystems and ecological infrastructure (*high confidence*) [8.2.4.5; 8.3.3.4]	Promotion of ecosystem restoration efforts consistent with the current degraded state of most of NYC's ecosystem function. A need exists for continued land use protection of the city's water supply region.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
Water supply systems (*medium confidence*) [8.3.3.4, 8.3.3.7]	NYC maintains an extremely extensive and resilient water supply infrastructure. Long-term adaptation could potentially include heightened drought management and interagency coordination with other water supply demand entities in region.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
Waste water system (*medium confidence*) [8.2.3.3,8.2.4.1]	NYC maintains an extremely extensive and resilient waste water infrastructure. Gray and green infrastructure adaptation to limit effects of extreme precipitation events and combined sewer overflows will be necessary.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
Energy systems (*medium confidence*) [8.2.4, 8.2.4.2]	NYC is served by an extensive energy generation and distribution system, most of which is operated by private companies or semi-public authorities. Peak load demand adaptation, especially for cooling demand will be necessary, as will adaptation for distribution disruptions associated with extreme events including ice storm events and coastal storm surge.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
Food systems and security (*medium confidence*) [8.3.3.2]	NYC is connected to a regional, national, and global food distribution system. Adaptation will be necessary to ensure that food processing and distribution systems within the city can be resilient in the face of potential extreme event impacts.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high

Continued next page →

Table 8-6 (continued)

New York City (continued)			
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe** / **Risk & potential for adaptation**
Transportation systems (*high confidence*) [8.2.2.2, 8.3.3.6]	NYC is served by a complex and redundant transportation and communications infrastructure. Numerous vulnerabilities to extreme events are present that result in short-term disruption. Long-term sea level rise and increased flood frequency can result in increased disruption and will require adaptation strategies.		
Housing (*high confidence*) [8.1.3, 8.2.4, 8.3.3.3]	NYC includes approximately 1 million buildings and similar structures. These maintain a broad range of vulnerabilities to climate change particularly associated with flooding and extreme heat events. Adaptation strategies could include retrofit construction practices, especially in coastal zone locations or areas affected by urban heat island conditions.		
Human health (*high confidence*) [8.2.3.1]	Great diversity of health conditions of the 8.3 plus million residents is associated with a wide range of human health vulnerabilities to climate change. The very young, aged, and otherwise health-compromised face heightened risk and require adaptation strategies, particularly focused on heat stress and disease.		
Key economic sectors and services (*medium confidence*) [8.3.3.1]	NYC has a diverse economic base focused on service-related industries with regional, national, and global connections. Adaptation will be necessary to limit vulnerability and enhance resilience in the face of large-scale extreme events such as Hurricane Sandy.		
Poverty and access to basic services (*medium confidence*) [8.3.3.8]	NYC has an extensive public service provision capacity. Adaptation will be necessary to ensure that more frequent or more intense extreme events will not limit this capacity.		

Alam, M. and M.D.G. Rabbani, 2007: Vulnerabilities and responses to climate change for Dhaka. *Environment and Urbanization*, **19(1)**, 81-97.

Allen, C. and S. Clouth, 2012: *A Guidebook to the Green Economy: Issue 1: Green Economy, Green Growth, and Low-Carbon Development*. United Nations Department of Economic and Social Affairs (UN DESA), Division for Sustainable Development, United Nations, New York, NY, USA, 64 pp.

Allen, L., F. Lindberg, and C. Grimmond, 2011: Global to city scale urban anthropogenic heat flux: model and variability. *International Journal of Climatology*, **31(13)**, 1990-2005.

Almansi, F., 2009: Regularizing land tenure within upgrading programmes in Argentina; the cases of Promeba and Rosario Hábitat. *Environment and Urbanization*, **21(2)**, 389-413.

ALNAP, 2012: *Responding to Urban Disasters: Learning from Previous Relief and Recovery Operations*. ALNAP Lessons Paper No. 5, The Active Learning Network for Accountability and Performance in Humanitarian Action (ALNAP) and Overseas Development Institute (ODI), London, UK, 30 pp.

Anguelovski, I. and J. Carmin, 2011: Something borrowed, everything new: innovation and institutionalization in urban climate governance. *Current Opinion in Environmental Sustainability*, **3(3)**, 169-175.

Annecke, W., 2010: Assessing vulnerability. *Tiempo: A Bulletin on Climate and Development*, **77**, 7-9.

Aon, 2013: *Global Risk Management Survey, 2013.* Aon Risk Solutions, Chicago, IL, USA, 122 pp.

Appadurai, A., 2001: Deep democracy: urban governmentality and the horizon of politics. *Environment and Urbanization*, **13(2)**, 23-43.

Aragón-Durand, F., 2008: *Estrategias de Protección Civil y Gestión de Riesgo Hidrometeorológico ante el Cambio Climático*. Instituto Nacional de Ecología (INE), Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT), SEMARNAT, Mexico, DF, Mexico, 97 pp.

Aragón-Durand, F., 2011: *Regional Workshop on Disaster Risk Reduction and Climate Change Adaptation in Urban Settings: From Theory to Practice.* Proceedings of the Workshop held in Tegucigalpa, Honduras, October 18 – 20, 2011, Adaptation Fund Board Secretariat (AFB), Ministry of Natural Resources and the Environment of the Government of the Republic of Honduras (SERNA), the Permanent Contingency Commission of Honduras (COPECO), European Commission (EC), Government of Switzerland, and United Nations Programme for Development-Honduras (PNUD-Honduras), 33 pp., www.preventionweb.net/english/professional/publications/v.php?id=24820

Aragón-Durand, F., 2012: *Análisis y Diseño de Medidas e Instrumentos de Respuesta del Sector Asegurador ante la Variabilidad Climática y el Cambio Climático en México.* Policy Report of the Programa de las Naciones Unidas para el Desarrollo (PNUD), Instituto Nacional de Ecología y Cambio Climático (INECC), Global Environment Facility (GEF) and Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT), México, DF, Mexico, 177 pp.

Archer, D., 2012: Finance as the key to unlocking community potential: savings, funds and the ACCA programme. *Environment and Urbanization*, **24(2)**, 423-440.

Archer, D. and S. Boonyabancha, 2011: Seeing a disaster as an opportunity – harnessing the energy of disaster survivors for change. *Environment and Urbanization*, **23(2)**, 351-364.

Arnbjerg-Nielsen, K., P. Willems, J. Olsson, S. Beecham, A. Pathirana, I. Bülow Gregersen, H. Madsen, and V. Nguyen, 2013: Impacts of climate change on rainfall extremes and urban drainage systems: a review. *Water Science and Technology*, **68(1)**, 16-28.

Arnell, N., 2009: Costs of adaptation in the water sector. In: *Assessing the Costs of Adaptation to Climate Change: A Review of the UNFCCC and other Recent Estimates* [Parry, M., N. Arnell, P. Berry, D. Dodman, S. Fankhauser, C. Hope, S. Kovats, R. Nicholls, D. Satterthwaite, R. Tiffin, and T. Wheeler (eds.)]. International Institute for Environment and Development (IIED) and Grantham Institute for Climate Change, London, UK, pp. 40-50.

Arup and C40, 2012: *Climate Action in Megacities: C40 Cities Baseline and Opportunities, Version 1.0*. Arup and C40 Cities Climate Leadership Group, New York, NY, USA, 110 pp.

Asariotis, R. and H. Benamara (eds.), 2012: *Maritime Transport and the Climate Change Challenge*. United Nations Conference on Trade and Development (UNCTAD), Co-published by the UN, New York, NY, USA and Earthscan (Routledge/Taylor & Francis), Abingdon, Oxon, UK, 327 pp.

Ashley, R., J. Blanskby, R. Newman, B. Gersonius, A. Poole, G. Lindley, S. Smith, S. Ogden, and R. Nowell, 2012: Learning and Action Alliances to build capacity for flood resilience. *Journal of Flood Risk Management*, **5(1)**, 14-22.

Athanassiadou, M., J. Baker, D. Carruthers, W. Collins, S. Girnary, D. Hassell, M. Hort, C. Johnson, K. Johnson, and R. Jones, 2010: An assessment of the impact of climate change on air quality at two UK sites. *Atmospheric Environment*, **44(15)**, 1877-1886.

Atteridge, A., C.K. Siebert, R.J. Klein, C. Butler, and P. Tella, 2009: *Bilateral Finance Institutions and Climate Change: A Mapping of Climate Portfolios*. Stockholm Environment Institute (SEI) Working Paper, 2009, Prepared for the United Nations Environment Programme Bilateral Finance Institutions Climate Change Working Group (UNEP BFI CCWG) and submitted to UNEP and the Agence Française de Développement (AFD), SEI, Stockholm, Sweden, 33 pp.

Awuor, C., V.Orindi, and A. Ochieng, 2008: Climate change and coastal cities: the case of Mombasa, Kenya. *Environment and Urbanization*, **20(1)**, 231-242.

Ayers, J., 2009: International funding to support urban adaptation to climate change. *Environment and Urbanization*, **21(1)**, 225-240.

Ayers, J.M. and S. Huq, 2009: The value of linking mitigation and adaptation: a case study of Bangladesh. *Environmental Management*, **43(5)**, 753-764.

Babel, M., A. Gupta, and N. Domingo, 2006: Land subsidence: a consequence of groundwater over-exploitation in Bangkok, Thailand. *International Review for Environmental Strategies*, **6(2)**, 307-327.

Backus, G.A., T.S. Lowry, and D.E. Warren, 2012: The near-term risk of climate uncertainty among the U.S. states. *Climatic Change*, **116(3-4)**, 495-522.

Baker, C., L. Chapman, A. Quinn, and K. Dobney, 2010: Climate change and the railway industry: a review. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, **224(3)**, 519-528.

Baker, J. (ed.), 2012: *Climate Change, Disaster Risk and the Urban Poor: Cities Building Resilience for a Changing World*. Urban Development Series, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 297 pp.

Balica, S., N. Wright, and F. Van der Meulen, 2012: A flood vulnerability index for coastal cities and its use in assessing climate change impacts. *Natural Hazards*, **64(1)**, 73-105.

Banks, N., 2008: A tale of two wards: political participation and the urban poor in Dhaka city. *Environment and Urbanization*, **20(2)**, 361-376.

Banks, N., M. Roy, and D. Hulme, 2011: Neglecting the urban poor in Bangladesh: research, policy and action in the context of climate change. *Environment and Urbanization*, **23(2)**, 487-502.

Barata, M., E. Ligeti, G. De Simone, T. Dickinson, D. Jack, J. Penney, M. Rahman, and R. Zimmerman, 2011: Climate change and human health in cities. In: *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, C., W.D. Solecki, S.A. Hammer, and S. Mehrotra (eds.)]. Cambridge University Press, Cambridge, UK, pp. 179-213.

Barnett, J. and W.N. Adger, 2007: Climate change, human security and violent conflict. *Political Geography*, **26(6)**, 639-655.

Bartlett, S., 2008: Climate change and urban children: impacts and implications for adaptation in low- and middle-income countries. *Environment and Urbanization*, **20(2)**, 501-519.

Battersby, J., 2013: Hungry cities: a critical review of urban food security research in sub-Saharan African cities. *Geography Compass*, **7(7)**, 452-463.

Becker, A., S. Inoue, M. Fischer, and B. Schwegler, 2012: Climate change impacts on international seaports: knowledge, perceptions, and planning efforts among port administrators. *Climatic Change*, **110(1)**, 5-29.

Bedsworth, L., 2009: Preparing for climate change: a perspective from local public health officers in California. *Environmental Health Perspectives*, **117(4)**, 617-623.

Bedsworth, L.W. and E. Hanak, 2010: Adaptation to climate change: a review of challenges and tradeoffs in six areas. *Journal of the American Planning Association*, **76(4)**, 477-495.

Beniston, M., 2010: Climate change and its impacts: growing stress factors for human societies. *International Review of the Red Cross*, **92(879)**, 557-568.

Benson, C. and E.J. Clay, 2004: *Understanding the Economic and Financial Impacts of Natural Disasters.* Disaster Risk Management Series No. 4, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 119 pp.

Benvenuti, S. and D. Bacci, 2010: Initial agronomic performances of Mediterranean xerophytes in simulated dry green roofs. *Urban Ecosystems*, **13(3)**, 349-363.

Benzie, M., A. Harvey, K. Burningham, N. Hodgson, and A. Siddiqi, 2011: *Vulnerability to Heatwaves and Drought: Adaptation to Climate Change*. Joseph Rowntree Foundation, York, UK, 86 pp.

Berger, F., 2003: Crise et reconversion dans la sidérurgie: étude comparée des bassins charbonniers de la Ruhr et du Nord-Pas-de-Calais. *Mitteilungsblatt* (Zeitschrift des Bochumer Instituts für soziale Bewegungen), **29**, 77-84.

Best Foot Forward, 2002: *City Limits: A Resource Flow and Ecological Footprint Analysis of Greater London*. Commissioned by IWM (EB), the Chartered Institution of Wastes Management Environmental Body, BFF, London, UK, 63 pp.

Betsill, M.M. and H. Bulkeley, 2004: Transnational networks and global environmental governance: the cities for climate protection program. *International Studies Quarterly*, **48(2)**, 471-493.

Betsill, M.M. and H. Bulkeley, 2006: Cities and the multilevel governance of global climate change. *Global Governance: A Review of Multilateralism and International Organizations*, **12(2)**, 141-159.

Bhat, G., A. Karanth, L. Dashora, and U. Rajasekar, 2013: Addressing flooding in the city of Surat beyond its boundaries. *Environment and Urbanization*, **25(2)**, 429-441.

Bicknell, J., D. Dodman, and D. Satterthwaite (eds.), 2009: *Adapting Cities to Climate Change: Understanding and Addressing the Development Challenges*. Earthscan, Abingdon, Oxon, UK and New York, NY, USA, 397 pp.

Birkmann, J., M. Garschagen, F. Kraas, and N. Quang, 2010: Adaptive urban governance: new challenges for the second generation of urban adaptation strategies to climate change. *Sustainability Science*, **5(2)**, 185-206.

Björnberg, K.E. and S.O. Hansson, 2013: Gendering local climate adaptation. *Local Environment*, **18(2)**, 217-232.

Blake, E.S., T.B. Kimberlain, R.J. Berg, J.P. Cangialosi, and J.L. Beven II, 2012: *Tropical Cyclone Report: Hurricane Sandy (AL182012), 22 – 29 October 2012*. National Hurricane Center, NOAA / National Weather Service, Miami, FL, USA, 157 pp.

Blake, R., A. Grimm, T. Ichinose, R. Horton, S. Gaffin, S. Jiong, D. Bader, and L. Cecil, 2011: Urban climate: processes, trends, and projections. In: *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, C., W. Solecki, S. Hammer, and S. Mehrotra (eds.)]. Cambridge University Press, Cambridge, UK, pp. 43-81.

Blanco, H., P. McCarney, S. Parnell, M. Schmidt, and K. Seto, 2011: The role of urban land in climate change. In: *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, C., W.D. Solecki, S.A. Hammer, and S. Mehrotra (eds.)]. Cambridge University Press, Cambridge, UK, pp. 217-248.

Blazejczyk, K., Y. Epstein, G. Jendritzky, H. Staiger, and B. Tinz, 2012: Comparison of UTCI to selected thermal indices. *International Journal of Biometeorology*, **56(3)**, 515-535.

Bloomberg, M.R. and R.T. Aggarwala, 2008: Think locally, act globally: how curbing global warming emissions can improve local public health. *American Journal of Preventive Medicine*, **35(5)**, 414-423.

Bloomberg, M.R. and C. Holloway, 2010: *NYC Green Infrastructure Plan: A Sustainable Strategy for Clean Waterways*. PlaNYC and NYC Department of Environmental Protection, New York, NY, USA, 141 pp.

BMA, GLF, and UNEP, 2009: *Bangkok Assessment Report on Climate Change.* Bangkok Metropolitan Administration (BMA), Green Leaf Foundation (GLF), and United Nations Environment Programme, (UNEP), BMA, Bangkok, Thailand, 88 pp.

Bohnenstengel, S., S. Evans, P.A. Clark, and S. Belcher, 2011: Simulations of the London urban heat island. *Quarterly Journal of the Royal Meteorological Society*, **137(659)**, 1625-1640.

Bolin, B., M. Seetharam, and B. Pompeii, 2010: Water resources, climate change, and urban vulnerability: a case study of Phoenix. *Local Environment*, **15(3)**, 261-279.

Bonazza, A., P. Messina, C. Sabbioni, C.M. Grossi, and P. Brimblecombe, 2009: Mapping the impact of climate change on surface recession of carbonate buildings in Europe. *Science of the Total Environment*, **407(6)**, 2039-2050.

Boonyabancha, S., 2005: Baan Mankong: going to scale with "slum" and squatter upgrading in Thailand. *Environment and Urbanization*, **17(1)**, 21-46.

Boonyabancha, S., 2009: Land for housing the poor – by the poor: experiences from the Baan Mankong nationwide slum upgrading programme in Thailand. *Environment and Urbanization*, **21(2)**, 309-329.

Boonyabancha, S. and D. Mitlin, 2012: Urban poverty reduction: learning by doing in Asia. *Environment and Urbanization*, **24(2)**, 403-421.

Bourque, A., A. Musy, and C. Larrivée, 2009: Ouranos: un modèle original pour le développement de connaissances menant à l'adaptation aux changements climatiques. *Liaison Énergie Francophonie*, **85**, 61-66.

Bowen, A. and J. Rydge, 2011: *Climate-Change Policy in the United Kingdom.* OECD Economics Department Working Paper No. 886, OECD Publishing, Paris, France, 42 pp.

Bowler, D.E., L. Buyung-Ali, T.M. Knight, and A.S. Pullin, 2010: Urban greening to cool towns and cities: a systematic review of the empirical evidence. *Landscape and Urban Planning*, **97(3)**, 147-155.

Brody, S., H. Grover, E. Lindquist, and A. Vedlitz, 2010: Examining climate change mitigation and adaptation behaviours among public sector organisations in the USA. *Local Environment*, **15(6)**, 591-603.

Brown, A., A. Dayal, and C.R. Del Rio, 2012: From practice to theory: emerging lessons from Asia for building urban climate change resilience. *Environment and Urbanization*, **24(2)**, 531-556.

Brown, D., 2011: Making the linkages between climate change adaptation and spatial planning in Malawi. *Environmental Science & Policy*, **14(8)**, 940-949.

Brown, J. and L. Peskett, 2011: *Looking at Effectiveness as well as Transparency in Climate Finance*. Opinion No. 9, European Development Co-operation to 2020 (EDEDC2020), European Association of Development Research and Training Institutes (EADI), Bonn, Germany, 2 pp.

Brown, S. and G. Walker, 2008: Understanding heat wave vulnerability in nursing and residential homes. *Building Research & Information*, **36(4)**, 363-372.

Brugmann, J., 2012: Financing the resilient city. *Environment and Urbanization*, **24(1)**, 215-232.

Brunner, R.D., 1996: Policy and global change research. *Climatic Change*, **32(2)**, 121-147.

Brunner, R.D., T. Steelman, L. Coe-Juell, C. Cromely, C. Edwards, and D. Tucker (eds.), 2005: *Adaptive Governance: Integrating Science, Policy, and Decision-Making*. Columbia University Press, New York, NY, USA, 319 pp.

Buchner, B., A. Falconer, M. Hervé-Mignucci, C. Trabacchi, and M. Brinkman, 2012: *The Landscape of Climate Finance 2012*. Climate Policy Initiative (CPI) Report, San Francisco, CA, USA, 84 pp.

Bulkeley, H., 2010: Cities and the governing of climate change. *Annual Review of Environment and Resources*, **35**, 229-253.

Bulkeley, H., 2013: *Cities and Climate Change*. Routledge, Abingdon, Oxon, UK and New York, NY, USA, 266 pp.

Bulkeley, H. and M. Betsill, 2005: Rethinking sustainable cities: multilevel governance and the 'urban' politics of climate change. *Environmental Politics*, **14(1)**, 42-63.

Bulkeley, H. and V. Castan Broto, 2013: Government by experiment? Global cities and the governing of climate change. *Transactions of the Institute of British Geographers*, **38(3)**, 361-375.

Bulkeley, H. and K. Kern, 2006: Local government and the governing of climate change in Germany and the UK. *Urban Studies*, **43(12)**, 2237-2259.

Bulkeley, H. and S.C. Moser, 2007: Responding to climate change: governance and social action beyond Kyoto. *Global Environmental Politics*, **7(2)**, 1-10.

Bulkeley, H. and R. Tuts, 2013: Understanding urban vulnerability, adaptation and resilience in the context of climate change. *Local Environment*, **18(6)**, 646-662.

Bulkeley, H., H. Schroeder, K. Janda, Z. Zhao, A. Armstrong, S.Y. Chi, and S. Ghosh, 2011: The role of institutions, governance, and urban planning for mitigation and adaptation. In: *Cities and Climate Change: Responding to an Urgent Agenda* [Hoornweg, D., M. Freire, M.J. Lee, P. Bhada-Tata, and B. Yuen (eds.)]. The International Bank for Reconstruction and Development / World Bank, Washington, DC, USA, pp. 125-160.

Bunce, M., S. Rosendo, and K. Brown, 2010: Perceptions of climate change, multiple stressors and livelihoods on marginal African coasts. *Environment, Development and Sustainability*, **12(3)**, 407-440.

Burch, S., 2010: Transforming barriers into enablers of action on climate change: insights from three municipal case studies in British Columbia, Canada. *Global Environmental Change*, **20(2)**, 287-297.

Burkart, K., A. Schneider, S. Breitner, M.H. Khan, A. Krämer, and W. Endlicher, 2011: The effect of atmospheric thermal conditions and urban thermal pollution on all-cause and cardiovascular mortality in Bangladesh. *Environmental Pollution*, **159(8)**, 2035-2043.

Burley, J.G., R.R. McAllister, K.A. Collins, and C.E. Lovelock, 2012: Integration, synthesis and climate change adaptation: a narrative based on coastal wetlands at the regional scale. *Regional Environmental Change*, **12(3)**, 581-593.

Buytaert, W., M. Vuille, A. Dewulf, R. Urrutia, A. Karmalkar, and R. Celleri, 2010: Uncertainties in climate change projections and regional downscaling in the tropical Andes: implications for water resources management. *Hydrology and Earth System Sciences*, **14(7)**, 1247-1258.

Cabannes, Y., 2004: Participatory budgeting: a significant contribution to participatory democracy. *Environment and Urbanization*, **16(1)**, 27-46.

Campbell, T., 2003: *Quiet Revolution: Decentralization and the Rise of Political Participation in Latin American Cities.* University of Pittsburgh Press, Pittsburgh, PA, USA, 208 pp.

Campbell-Lendrum, D. and C. Corvalan, 2007: Climate change and developing-country cities: implications for environmental health and equity. *Journal of Urban Health*, **84(1)**, 109-117.

Cannon, T., 1994: Vulnerability analysis and the explanation of 'natural' disasters'. In: *Disasters, Development and Environment* [Varley, A. (ed.)]. John Wiley and Sons, Chichester, UK, pp. 13-30.

Carbognin, L., P. Teatini, A. Tomasin, and L. Tosi, 2010: Global change and relative sea level rise at Venice: what impact in term of flooding. *Climate Dynamics*, **35(6)**, 1039-1047.

Carcellar, N., J.C.R. Co, and Z.O. Hipolito, 2011: Addressing disaster risk reduction through community-rooted interventions in the Philippines: experience of the Homeless People's Federation of the Philippines. *Environment and Urbanization*, **23(2)**, 365-381.

Carmin, J., D. Roberts, and D. Anguelovski, 2009: *Planning Climate Resilient Cities: Early Lessons from Early Adopters.* Presentation for the "Government Institutions and Innovations in Governance for Achieving Climate Adaptation in Cities" Session, Proceedings of the World Bank Fifth Urban Research Symposium – Cities and Climate Change: Responding to an Urgent Agenda, 28-30 June 2009, Marseilles, France, 27 pp.

Carmin, J., N. Nadkarni, and C. Rhie, 2012a: *Progress and Challenges in Urban Climate Adaptation Planning: Results of a Global Survey*. Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, 30 pp.

Carmin, J., I. Anguelovski, and D. Roberts, 2012b: Urban climate adaptation in the global south planning in an emerging policy domain. *Journal of Planning Education and Research*, **32(1)**, 18-32.

Carmin, J., E. Chu, and D. Dodman, 2013: *Urban Climate Adaptation and Leadership: From Conceptual to Practical Understanding*. OECD Regional Development Working Paper No. 2013/26, OECD Publishing, Paris, France, 48 pp., doi:10.1787/5k3ttg88w8hh-en.

Carter, J.G., 2011: Climate change adaptation in European cities. *Current Opinion in Environmental Sustainability*, **3(3)**, 193-198.

Cartwright, A., S. Parnell, G. Oelofse, and S. Ward, 2012: *Climate Change at the City Scale: Impacts, Mitigation and Adaptation in Cape Town.* Routledge, Abingdon, Oxon, UK, 277 pp.

Cartwright, A., J. Blignaut, M. De Wit, K. Goldberg, M. Mander, S. O'Donoghue, and D. Roberts, 2013: Economics of climate change adaptation at the local scale under conditions of uncertainty and resource constraints: the case of Durban, South Africa. *Environment and Urbanization*, **25(1)**, 139-156.

Carvalho, A. and J. Burgess, 2005: Cultural circuits of climate change in UK broadsheet newspapers, 1985-2003. *Risk Analysis*, **25(6)**, 1457-1469.

Cash, D.W. and S.C. Moser, 2000: Linking global and local scales: designing dynamic assessment and management processes. *Global Environmental Change*, **10(2)**, 109-120.

Cash, D.W., W.C. Clark, F. Alcock, N.M. Dickson, N. Eckley, D.H. Guston, J. Jäger, and R.B. Mitchell, 2003: Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences of the United States of America*, **100(14)**, 8086-8091.

Cash, D.W., W.N. Adger, F. Berkes, P. Garden, L. Lebel, P. Olsson, L. Pritchard, and O. Young, 2006: Scale and cross-scale dynamics: governance and information in a multilevel world. *Ecology and Society*, **11(2)**, 1-12.

Cashman, A., L. Nurse, and C. John, 2010: Climate change in the Caribbean: the water management implications. *The Journal of Environment & Development*, **19(1)**, 42-67.

Castán Broto, V., B. Oballa, and P. Junior, 2013: Governing climate change for a just city: challenges and lessons from Maputo, Mozambique. *Local Environment*, **18(6)**, 678-704.

Castleton, H.F., V. Stovin, S.B.M. Beck, and J.B. Davison, 2010: Green roofs; building energy savings and the potential for retrofit. *Energy and Buildings*, **42(10)**, 1582-1591.

CEPAL, 2008: *Tabasco: Características e Impacto Socio-Económico de las Inundaciones Provocadas a Finales de Octubre y a Comienzos de Noviembre de 2007 por el Frente Frío Número 4*. La Sede Subregional de la Comisión Económica para América Latina y el Caribe (CEPAL) en México, Mexico, DF, Mexico, 231 pp.

Chambers, R., 1989: Editorial introduction: vulnerability, coping and policy. *IDS Bulletin*, **20(2)**, 1-7.

Chance, T., 2009: Towards sustainable residential communities; the Beddington Zero Energy Development (BedZED) and beyond. *Environment and Urbanization*, **21(2)**, 527-544.

Chang, H., M. Lafrenz, I. Jung, M. Figliozzi, D. Platman, and C. Pederson, 2010: Potential impacts of climate change on flood-induced travel disruptions: a case study of Portland, Oregon, USA. *Annals of the Association of American Geographers*, **100(4)**, 938-952.

Chang, S.E., T.L. McDaniels, J. Mikawoz, and K. Peterson, 2007: Infrastructure failure interdependencies in extreme events: power outage consequences in the 1998 Ice Storm. *Natural Hazards*, **41(2)**, 337-358.

Chapman, L., J.A.D. Azevedo, and T. Prieto-Lopez, 2013: Urban heat & critical infrastructure networks: a viewpoint. *Urban Climate*, **3(May)**, 7-12.

Charlton, M.B. and N.W. Arnell, 2011: Adapting to climate change impacts on water resources in England – an assessment of draft Water Resources Management Plans. *Global Environmental Change*, **21(1)**, 238-248.

Chaum, M., J. Brown, B. Buchner, A. Falconer, C. Faris, K. Sierra, C. Trabacchi, and G. Wagner, 2011: *Improving the Effectiveness of Climate Finance: Key Lessons*. Brookings Institution, Overseas Development Institute (ODI), Climate Policy Initiative (CPI), and the Environmental Defense Fund (EDF), CPI, San Francisco, CA, USA, 15 pp.

Chen, J., Q. Li, J. Niu, and L. Sun, 2011: Regional climate change and local urbanization effects on weather variables in Southeast China. *Stochastic Environmental Research and Risk Assessment*, **25(4)**, 555-565.

Chevallier, P., B. Pouyaud, W. Suarez, and T. Condom, 2011: Climate change threats to environment in the tropical Andes: glaciers and water resources. *Regional Environmental Change*, **11(1)**, 179-187.

City of Boston, 2011: *A Climate of Progress: City of Boston Climate Action Plan Update 2011*. City of Boston, Boston, MA, USA, 43 pp.

City of Cape Town, 2006: *Framework for Adaptation to Climate Change in the City of Cape Town (FAC^{4}T)*. City of Cape Town, Cape Town, South Africa, 66 pp.

City of Chicago, 2008: *Chicago Climate Action Plan 2008: Our City, Our Future.* City of Chicago, Chicago, IL, USA, 56 pp.

City of Chicago, 2010: *Chicago Climate Change Action Plan 2010*, *Chicago Climate Action Plan Progress Report – First Two Years.* City of Chicago, Department of Environment, Chicago, IL, USA, 13 pp.

City of Melbourne, 2009: *Climate Change Adaptation Strategy*. City of Melbourne, Melbourne, Australia, 128 pp.

City of New York, 2011: *PlaNYC: A Greener, Greater New York. Update April 2011*. City of New York, New York, NY, USA, 200 pp.

City of Toronto, 2013: *Hot Weather Response Plan*. Toronto Public Health, City of Toronto, Toronto, Ontario, Canada, 13 pp., www.toronto.ca/health/heatalerts/pdf/hwr_plan_2013.pdf.

Chrysoulakis, N., M. Lopes, R. San José, C.S.B. Grimmond, M.B. Jones, V. Magliulo, J.E. Klostermann, A. Synnefa, Z. Mitraka, and E.A. Castro, 2013: Sustainable urban metabolism as a link between bio-physical sciences and urban planning: the BRIDGE project. *Landscape and Urban Planning*, **112**, 100-117.

Chu, S.Y. and H. Schroeder, 2010: Private governance of climate change in Hong Kong: an analysis of drivers and barriers to corporate action. *Asian Studies Review*, **34(3)**, 287-308.

Cissé, G., B. Koné, H. Bâ, I. Mbaye, K. Koba, J. Utzinger, and M. Tanner, 2011: Ecohealth and climate change: adaptation to flooding events in riverside secondary cities, West Africa. In: *Resilient Cities: Cities and Adaptation to Climate Change - Proceedings of the Global Forum 2010* [Otto-Zimmermann, K. (ed.)]. Springer, Dordrecht, Netherlands, pp. 55-67.

Clapp, C., J. Ellis, J. Benn, and J. Corfee-Morlot, 2012: *Tracking Climate Finance: What and How?* COM/ENV/EPOC/IEA/SLT(2012)1, Organisation for Economic Co-operation and Development (OECD) and International Energy Agency (IEA), OECD/IEA Publishing, Paris, France, 42 pp.

Clapp, C., A. Leseur, O. Sartor, G. Briner, and J. Corfee-Morlot, 2010: *Cities and Carbon Market Finance: Taking Stock of Cities' Experience with CDM and JI.* OECD Environmental Working Paper No. 29, OECD Publishing, Paris, France, 81 pp.

Cohen, M.J. and J.L. Garrett, 2010: The food price crisis and urban food (in)security. *Environment and Urbanization*, **22(2)**, 467-482.

Colby, B.G. and K.L. Jacobs, 2007: *Arizona Water Policy: Management Innovations in an Urbanizing, Arid Region*. Issues in Water Resources Policy Series, Resources for the Future, Washington, DC, USA, 247 pp.

Corburn, J., 2009: Cities, climate change and urban heat island mitigation: localising global environmental science. *Urban Studies*, **46(2)**, 413-427.

Corfee-Morlot, J., I. Cochran, S. Hallegatte, and P. Teasdale, 2011: Multilevel risk governance and urban adaptation policy. *Climatic Change*, **104(1)**, 169-197.

Crawford, K., M. Suvatne, J. Kennedy, and T. Corsellis, 2010: Urban shelter and the limits of humanitarian action. *Forced Migration Review*, **34**, 27-28.

Crush, J., B. Frayne, and W. Pendleton, 2012: The crisis of food insecurity in African cities. *Journal of Hunger & Environmental Nutrition*, **7(2-3)**, 271-292.

d'Cruz, C. and P. Mudimu, 2013: Community savings that mobilize federations, build women's leadership and support slum upgrading. *Environment and Urbanization*, **25(1)**, 31-45.

da Silva, J., 2010: *Lessons from Aceh: Key Considerations in Post-Disaster Reconstruction*. The Disasters Emergency Committe and Ove Arup Partners Ltd., Practical Action Publishing Limited, Rugby, UK, 94 pp.

da Silva, J., 2012: *Shifting Agendas: Response to Resilience. The Role of the Engineer in Disaster Risk Reduction.* 9th Brunel International Lecture Series, Institution of Civil Engineers, London, UK, 43 pp.

da Silva, J., S. Kernaghan, and A. Luque, 2012: A systems approach to meeting the challenges of urban climate change. *International Journal of Urban Sustainable Development*, **4(2)**, 125-145.

Dawson, J.P., B.J. Bloomer, D.A. Winner, and C.P. Weaver, 2013: Understanding the meteorological drivers of US particulate matter concentrations in a changing climate. *Bulletin of the American Meteorological Society*, doi.org/10.1175/BAMS-D-12-00181.1.

Dawson, R.J., J.W. Hall, S.L. Barr, M. Batty, A.L. Bristow, S. Carney, A. Dagoumas, S. Evans, A.C. Ford, J. Köhler, M.R. Tight, C.L. Walsh, H. Watters, and A.M. Zanni, 2009: A blueprint for the integrated assessment of climate change in cities. In: *Green CITYnomics: The Urban War against Climate Change* [Tang, K. (ed.)]. Greenleaf Publishing, Sheffield, UK, pp. 32-52.

de Lucena, A.F.P., A.S. Szklo, R. Schaeffer, R.R. de Souza, B.S.M.C. Borba, I.V.L. da Costa, A.O.P. Júnior, and S.H.F. da Cunha, 2009: The vulnerability of renewable energy to climate change in Brazil. *Energy Policy*, **37(3)**, 879-889.

de Lucena, A.F.P., R. Schaeffer, and A.S. Szklo, 2010: Least-cost adaptation options for global climate change impacts on the Brazilian electric power system. *Global Environmental Change*, **20(2)**, 342-350.

de Sherbinin, A., A. Schiller, and A. Pulsipher, 2007: The vulnerability of global cities to climate hazards. *Environment and Urbanization*, **19(1)**, 39-64.

de Sherbinin, A., M. Castro, F. Gemenne, M. Cernea, S. Adamo, P. Fearnside, G. Krieger, S. Lahmani, A. Oliver-Smith, and A. Pankhurst, 2011: Preparing for resettlement associated with climate change. *Science*, **334(6055)**, 456-457.

Deak, J. and E. Bucht, 2011: Planning for climate change: the role of indigenous blue infrastructure, with a case study in Sweden. *Town Planning Review*, **82(6)**, 669-685.

Depietri, Y., F.G. Renaud, and G. Kallis, 2012: Heat waves and floods in urban areas: a policy-oriented review of ecosystem services. *Sustainability Science*, **7(1)**, 95-107.

Diagne, K., 2007: Governance and natural disasters: addressing flooding in Saint Louis, Senegal. *Environment and Urbanization*, **19(2)**, 552-562.

Dietz, T., E. Ostrom, and P.C. Stern, 2003: The struggle to govern the commons. *Science*, **302(5652)**, 1907-1912.

Dobney, K., C. Baker, A. Quinn, and L. Chapman, 2008: Quantifying the effects of high summer temperatures due to climate change on buckling and rail related delays in south-east United Kingdom. *Meteorological Applications*, **16(2)**, 245-251.

Dodman, D., 2009: Blaming cities for climate change? An analysis of urban greenhouse gas emissions inventories. *Environment and Urbanization*, **21(1)**, 185-201.

Dodman, D. and D. Mitlin, 2011: Challenges for community-based adaptation: discovering the potential for transformation. *Journal of International Development*, **25(5)**, 640-659.

Dodman, D. and D. Satterthwaite, 2009: The costs of adapting infrastructure to climate change. In: *Assessing the Costs of Adaptation to Climate Change: A Review of the UNFCCC and Other Recent Estimates* [Parry, M., N. Arnell, P. Berry, D. Dodman, S. Fankhauser, C. Hope, S. Kovats, R. Nicholls, D. Satterthwaite, R. Tiffin, and T. Wheeler (eds.)]. IIED and Grantham Institute for Climate Change, London, UK, pp. 73-89.

Dossou, K.M.R. and B. Gléhouenou-Dossou, 2007: The vulnerability to climate change of Cotonou (Benin): the rise in sea level. *Environment and Urbanization*, **19(1)**, 65-79.

Douglas, I., 2009: Climate change, flooding and food security in south Asia. *Food Security*, **1(2)**, 127-136.

Douglas, I., K. Alam, M. Maghenda, Y. Mcdonnell, L. Mclean, and J. Campbell, 2008: Unjust waters: climate change, flooding and the urban poor in Africa. *Environment and Urbanization*, **20(1)**, 187-205.

Douglass, M., 2002: From global intercity competition to cooperation for livable cities and economic resilience in Pacific Asia. *Environment and Urbanization*, **14(1)**, 53-68.

Drejza, S., P. Bernatchez, and C. Dugas, 2011: Effectiveness of land management measures to reduce coastal georisks, eastern Québec, Canada. *Ocean & Coastal Management*, **54(4)**, 290-301.

Eakin, H., V. Magaña, J. Smith, J.L. Moreno, J.M. Martínez, and O. Landavazo, 2007: A stakeholder driven process to reduce vulnerability to climate change in Hermosillo, Sonora, Mexico. *Mitigation and Adaptation Strategies for Global Change*, **12(5)**, 935-955.

Eakin, H., A.M. Lerner, and F. Murtinho, 2010: Adaptive capacity in evolving peri-urban spaces: Responses to flood risk in the Upper Lerma River Valley, Mexico. *Global Environmental Change*, **20(1)**, 14-22.

Ebi, K.L. and J.A. Paulson, 2010: Climate change and child health in the United States. *Current Problems in Pediatric and Adolescent Health Care*, **40(1)**, 2-18.

EEA, 2012: *Urban Adaptation to Climate Change in Europe: Challenges and Opportunities for Cities Together with Supportive National and European Policies.* EEA Report, No. 2/2012, European Environment Agency (EEA), Copenhagen, Denmark, 143 pp.

Egondi, T., C. Kyobutungi, S. Kovats, K. Muindi, R. Ettarh, and J. Rocklöv, 2012: Time-series analysis of weather and mortality patterns in Nairobi's informal settlements. *Global Health Action*, **5**, 23-32.

Eichhorst, U., 2009: *Adapting Urban Transport to Climate Change, Module 5f. Sustainable Transport: A Sourcebook for Policy-makers in Developing Cities*. Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ), Division 313 – Water, Energy, Urban Development, GTZ, Eschborn, Germany, 62 pp.

El Banna, M.M. and O.E. Frihy, 2009: Natural and anthropogenic influences in the northeastern coast of the Nile delta, Egypt. *Environmental Geology*, **57(7)**, 1593-1602.

Ellis, E.C., K.K. Goldewijk, S. Siebert, D. Lightman, and N. Ramankutty, 2010: Anthropogenic transformation of the biomes, 1700 to 2000. *Global Ecology and Biogeography*, **19**, 589-606.

Engineering the Future, 2011: *Infrastructure, Engineering and Climate Change Adaptation: Ensuring Services in an Uncertain Future*. Royal Academy of Engineering, London, UK, 107 pp.

Engineers Canada, 2008: *Adapting to Climate Change: Canada's First National Engineering Vulnerability Assessment and Adaptation to a Changing Climate*. Engineers Canada, Ottawa, Ontario, Canada, 76 pp.

EPA, 2013: *Climate Ready Water Utilities: Adaptation Strategies Guide for Water Utilities*. EPA 817-K-13-001, Office of Water (4608-T), United States Environmental Protection Agency (EPA), Washington, DC, USA, 106 pp.

Ernstson, H., S.E. van der Leeuw, C.L. Redman, D.J. Meffert, G. Davis, C. Alfsen, and T. Elmqvist, 2010: Urban transitions: on urban resilience and human-dominated ecosystems. *AMBIO: A Journal of the Human Environment*, **39(8)**, 531-545.

Eurocontrol, 2008: *The Challenges of Growth: Air Traffic Statistics and Forecasts.* European Organisation for the Safety of Air Navigation (EUROCONTROL), Brussels, Belgium, 40 pp.

Fane, S. and A. Turner, 2010: Integrated water resource planning in the context of climate uncertainty. *Water Science and Technology: Water Supply*, **10(4)**, 487-494.

Fankhauser, S., 2010: The costs of adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, **1(1)**, 23-30.

Fankhauser, S. and R. Soare, 2013: An economic approach to adaptation: illustrations from Europe. *Climatic Change*, **118(2)**, 367-379.

Fankhauser, S., S. Agrawala, D. Hanrahan, D. Pope, J. Skees, C. Stephens, and S. Yearley, 2008: Economic and policy instruments to promote adaptation. In: *Economic Aspects of Adaptation to Climate Change: Costs, Benefits and Policy Instruments* [Agrawala, S. and S. Fankhauser (eds.)]. OECD, Paris, France, pp. 85-133.

Farley, K.A., C. Tague, and G.E. Grant, 2011: Vulnerability of water supply from the Oregon Cascades to changing climate: linking science to users and policy. *Global Environmental Change*, **21(1)**, 110-122.

Fazey, I., M. Kesby, A. Evely, I. Latham, D. Wagatora, J. Hagasua, M.S. Reed, and M. Christie, 2010: A three-tiered approach to participatory vulnerability assessment in the Solomon Islands. *Global Environmental Change*, **20(4)**, 713-728.

Ferguson, B. and J. Navarrete, 2003: A financial framework for reducing slums: lessons from experience in Latin America. *Environment and Urbanization*, **15(2)**, 201-216.

Fergutz, O., S. Dias, and D. Mitlin, 2011: Developing urban waste management in Brazil with waste picker organizations. *Environment and Urbanization*, **23(2)**, 597-608.

Fernandes, E., 2007: Implementing the urban reform agenda in Brazil. *Environment and Urbanization*, **19(1)**, 177-189.

Finland Safety Investigations Authority, 2011: *S2/2010Y The Storms of July-August 2010*. Finland Safety Investigations Authority, Helsinki, Finland, 158 pp., www.turvallisuustutkinta.fi/en/1279614262854.

Flanner, M.G., 2009: Integrating anthropogenic heat flux with global climate models. *Geophysical Research Letters*, **36(2)**, L02801, doi:10.1029/2008GL036465.

Foster, J., A. Lowe, and S. Winkelman, 2011a: *Lessons Learned on Local Climate Adaptation from the Urban Leaders Adaptation Initiatives*. The Center for Clean Air Policy (CCAP), Washington, DC, USA, 21 pp.

Foster, J., A. Lowe, and S. Winkelman, 2011b: *The Value of Green Infrastructure for Urban Climate Adaptation*. The Center for Clean Air Policy (CCAP), Washington, DC, USA, 52 pp.

Früh, B., P. Becker, T. Deutschländer, J. Hessel, M. Kossmann, I. Mieskes, J. Namyslo, M. Roos, U. Sievers, and T. Steigerwald, 2011: Estimation of climate-change impacts on the urban heat load using an urban climate model and regional climate projections. *Journal of Applied Meteorology and Climatology*, **50(1)**, 167-184.

Frumkin, H., J. Hess, G. Luber, J. Malilay, and M. McGeehin, 2008: Climate change: the public health response. *American Journal of Public Health*, **98(3)**, 435-445.

Fujibe, F., 2008: Detection of urban warming in recent temperature trends in Japan. *International Journal of Climatology*, **29(12)**, 1811-1822.

Fujibe, F., 2011: Urban warming in Japanese cities and its relation to climate change monitoring. *International Journal of Climatology*, **31(2)**, 162-173.

Funtowicz, S.O. and J.R. Ravetz, 1993: Science for the post-normal age. *Futures*, **25(7)**, 739-755.

Gaffin, S.R., C. Rosenzweig, and A.Y. Kong, 2012: Adapting to climate change through urban green infrastructure. *Nature Climate Change*, **2(10)**, 704-704.

Gamble, J., M. Stevenson, E. McClean, and L.G. Heaney, 2009: The prevalence of non-adherence in difficult asthma. *American Journal of Respiratory and Critical Care Medicine*, **180(9)**, 817-822.

Garschagen, M., 2013: Resilience and organisational institutionalism from a cross-cultural perspective – an exploration based on urban climate change adaptation in Vietnam. *Natural Hazards*, **67(1)**, 25-46.

Garschagen, M. and F. Kraas, 2011: Urban climate change adaptation in the context of transformation – lessons learned from Vietnam. In: *Resilient Cities: Cities and Adaptation to Climate Change, Proceedings of the Global Forum 2010* [Otto-Zimmermann, K. (ed.)]. Springer, Dordrecht, Netherlands, pp. 131-139.

Gasper, R., A. Blohm, and M. Ruth, 2011: Social and economic impacts of climate change on the urban environment. *Current Opinion in Environmental Sustainability*, **3(3)**, 150-157.

Gavidia, J., 2006: Priority goals in Central America. The development of sustainable mechanisms for participation in local risk management. Special edition for the 3rd World Urban Forum, UN-HABITAT, Vancouver, June 2006, *Milenio Ambiental*, **S4**, 56-59, [Journal of the Urban Environment Programme (UPE), of the International Development Research Center (IDRC), Montevideo, Uruguay], idl-bnc.idrc.ca/dspace/bitstream/10625/39513/1/2006_06_no4.pdf.

GDF, 2006: *Estrategia Local de Acción Climática del Distrito Federal.* El Gobierno del Distrito Federal (GDF), Secretaría del Medio Ambiente del Distrito Federal, Mexico, DF, Mexico, 214 pp.

GDF, 2008: *Programa de Acción Climática de la Ciudad de México 2008-2012.* El Gobierno del Distrito Federal (GDF), Secretaría del Medio Ambiente del Distrito Federal, Mexico, DF, Mexico, 172 pp.

Getter, K.L., D.B. Rowe, J.A. Andresen, and I.S. Wichman, 2011: Seasonal heat flux properties of an extensive green roof in a Midwestern U.S. climate. *Energy and Buildings*, **43(12)**, 3548-3557.

GFDRR, 2009: *Integrating Disaster Risk Reduction into the Fight against Poverty: Annual Report 2009*. Global Facility for Disaster Reduction and Recovery (GFDRR), GFDRR Secretariat, Washington, DC, USA, 71 pp.

GFDRR, 2013: *Managing Disaster Risks for a Resilient Future: A Work Plan for the Global Facility for Disaster Reduction and Recovery 2014-2016*. Global Facility for Disaster Reduction and Recovery (GFDRR), GFDRR Secretariat, Washington, DC, USA, 58 pp.

Gieryn, T.F., 1999: *Cultural Boundaries of Science: Credibility on the Line.* University of Chicago Press, Chicago, IL, USA, 398 pp.

Giguère, M., 2009: *Mesures de Lutte aux Îlots de Chaleur Urbains: Revue de Littérature. Direction des Risques Biologiques, Environnementaux et Occupationnels*. N° de publication: 988, Gouvernement du Québec, Institut National de Santé Publique Québec, Québec, QC, Canada, 77 pp.

Gill, S., J. Handley, A. Ennos, and S. Pauleit, 2007: Adapting cities for climate change: the role of the green infrastructure. *Built Environment*, **33(1)**, 115-133.

GLA, 2008: *The London Climate Change Adaptation Strategy: Draft Report*. Greater London Authority (GLA), London, UK, 113 pp.

GLA, 2010: *The Draft Climate Change Adaptation Strategy for London: Public Consultation Draft*. Greater London Authority (GLA), London, UK, 136 pp.

GLA, 2011: *Managing Risks and Increasing Resilience: The Mayor's Climate Change Adaptation Strategy*. Greater London Authority (GLA), London, UK, 123 pp.

Gober, P., 2010: Desert urbanization and the challenges of water sustainability. *Current Opinion in Environmental Sustainability*, **2(3)**, 144-150.

Gober, P., C.W. Kirkwood, R.C. Balling, A.W. Ellis, and S. Deitrick, 2010: Water planning under climatic uncertainty in Phoenix: why we need a new paradigm. *Annals of the Association of American Geographers*, **100(2)**, 356-372.

Godfray, H.C.J., J.R. Beddington, I.R. Crute, L. Haddad, D. Lawrence, J.F. Muir, J. Pretty, S. Robinson, S.M. Thomas, and C. Toulmin, 2010: Food security: the challenge of feeding 9 billion people. *Science*, **327(5967)**, 812-818.

Government of South Africa, 2010: *National Climate Change Response Green Paper*. Government of the Republic of South Africa, Ministry of Water and Environmental Affairs, Department of Environmental Affairs, Pretoria, South Africa, 38 pp.

Granberg, M. and I. Elander, 2007: Local governance and climate change: reflections on the Swedish experience. *Local Environment*, **12(5)**, 537-548.

Grimm, N.B., S.H. Faeth, N.E. Golubiewski, C.L. Redman, J. Wu, X. Bai, and J.M. Briggs, 2008: Global Change and the ecology of cities. *Science*, **319(5864)**, 756-760.

Grimmond, C.S.B., 2011: Climate of cities. In: *Routledge Handbook of Urban Ecology* [Douglas, I., D. Goode, M. Houck, and R. Wang (eds.)]. Routledge, Abingdon, UK, pp. 103-119.

Grindle, M.S. and J.W. Thomas, 1991: *Public Choices and Policy Change: The Political Economy of Reform in Developing Countries.* Johns Hopkins University Press, Baltimore, MD, USA, 222 pp.

Grossi, C.M., P. Brimblecombe, and I. Harris, 2007: Predicting long term freeze–thaw risks on Europe built heritage and archaeological sites in a changing climate. *Science of the Total Environment*, **377(2-3)**, 273-281.

Gupta, J., R. Lasage, and T. Stam, 2007: National efforts to enhance local climate policy in the Netherlands. *Environmental Sciences*, **4(3)**, 171-182.

Gurran, N., E. Hamin, and B. Norman, 2012: Climate change mitigation, adaptation and local planning. In: *Australian Urban Land Use Planning: Principles and Practice* [Gurran, N. (ed.)]. Sydney University Press, Sydney, Australia, pp. 237-250.

Gusdorf, F., S. Hallegatte, and A. Lahellec, 2008: Time and space matter: how urban transitions create inequality. *Global Environmental Change*, **18(4)**, 708-719.

Hacker, J.N. and M.J. Holmes, 2007: Thermal comfort: climate change and the environmental design of buildings in the United Kingdom. *Built Environment*, **33(1)**, 97-114.

Hahn, M.B., A.M. Riederer, and S.O. Foster, 2009: The livelihood vulnerability index: a pragmatic approach to assessing risks from climate variability and change – a case study in Mozambique. *Global Environmental Change*, **19(1)**, 74-88.

Haines, A., N. Bruce, S. Cairncross, M. Davies, K. Greenland, A. Hiscox, S. Lindsay, T. Lindsay, D. Satterthwaite, and P. Wilkinson, 2013: Promoting health and advancing development through improved housing in low-income settings. *Journal of Urban Health*, **90(5)**, 810-831.

Hajat, S., M. O'Connor, and T. Kosatsky, 2010: Health effects of hot weather: from awareness of risk factors to effective health protection. *The Lancet*, **375(9717)**, 856-863.

Hall, J., J. Henriques, A. Hickford, and R. Nicholls, 2012: *A Fast Track Analysis of Strategies for Infrastructure Provision in Great Britain: Executive Summary*. Environmental Change Institute, University of Oxford, Oxford, UK, 19 pp.

Hall, J.W., R.J. Dawson, S.L. Barr, M. Batty, A.L. Bristow, S. Carney, A. Dagoumas, A. Ford, C. Harpham, M.R. Tight, C.L. Walsh, H. Watters, and A.M. Zanni, 2010: City-scale integrated assessment of climate impacts, adaptation and mitigation. In: *Energy Efficient Cities: Assessment Tools and Benchmarking Practices* [Bose, R.K. (ed.)]. World Bank, Washington, DC, USA, pp. 43-64.

Hallegatte, S. and J. Corfee-Morlot, 2011: Understanding climate change impacts, vulnerability and adaptation at city scale: an introduction. *Climatic Change*, **104(1)**, 1-12.

Hallegatte, S., J. Hourcade, and P. Ambrosi, 2007a: Using climate analogues for assessing climate change economic impacts in urban areas. *Climatic Change*, **82(1)**, 47-60.

Hallegatte, S., J. Hourcade, and P. Dumas, 2007b: Why economic dynamics matter in assessing climate change damages: illustration on extreme events. *Ecological Economics*, **62(2)**, 330-340.

Hallegatte, S., F. Henriet, A. Patwardhan, K. Narayanan, S. Ghosh, S. Karmakar, U. Patnaik, A. Abhayankar, S. Pohit, and J. Corfee-Morlot, 2010: *Flood Risks, Climate Change Impacts and Adaptation Benefits in Mumbai: An Initial Assessment of Socio-Economic Consequences of Present and Climate Change Induced Flood Risks and of Possible Adaptation Options*. OECD Environment Working Papers No. 27, OECD Publishing, Paris, France, 61 pp.

Hallegatte, S., F. Henriet, and J. Corfee-Morlot, 2011a: The economics of climate change impacts and policy benefits at city scale: a conceptual framework. *Climatic Change*, **104(1)**, 51-87.

Hallegatte, S., N. Ranger, O. Mestre, P. Dumas, J. Corfee-Morlot, C. Herweijer, and R.M. Wood, 2011b: Assessing climate change impacts, sea level rise and storm surge risk in port cities: a case study on Copenhagen. *Climatic Change*, **104(1)**, 113-137.

Hallegatte, S., C. Green, R.J. Nicholls, and J. Corfee-Morlot, 2013: Future flood losses in major coastal cities. *Nature Climate Change*, **3(9)**, 802-806.

Halsnæs, K. and A. Garg, 2011: Assessing the role of energy in development and climate policies – conceptual approach and key indicators. *World Development*, **39(6)**, 987-1001.

Halsnæs, K. and S. Trærup, 2009: Development and climate change: a mainstreaming approach for assessing economic, social, and environmental impacts of adaptation measures. *Environmental Management*, **43(5)**, 765-778.

Hamdan, M.A., J. Yamin, and E.A. Abdelhafez, 2012: Passive cooling roof design under Jordanian climate. *Sustainable Cities and Society*, **5**, 26-29.

Hamin, E.M. and N. Gurran, 2009: Urban form and climate change: Balancing adaptation and mitigation in the U.S. and Australia. *Habitat International*, **33(3)**, 238-245.

Hammer, S., J. Keirstead, S. Dhakal, J. Mitchell, M. Coley, R. Connell, R. Gonzalez, L. Herve-Mignucci, L. Parshall, N. Schulz, and M. Hyams, 2011: Climate change and urban energy systems. In: *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, C., W.D. Solecki, S.A. Hammer, and S. Mehrotra (eds.)]. Cambridge University Press, Cambridge, UK, pp. 85-111.

Hammill, A. and T. Tanner, 2011: *Harmonising Climate Risk Management: Adaptation Screening and Assessment Tools for Development Co-operation.* OECD Environment Working Paper No. 36, OECD Publishing, Paris, France, 52 pp.

Hammill, A., M. Richard, and E. McCarter, 2008: Microfinance and climate change adaptation. *IDS Bulletin*, **39(4)**, 113-122.

Hanak, E. and J. Lund, 2012: Adapting California's water management to climate change. *Climatic Change*, **111(1)**, 17-44.

Hanson, S., R. Nicholls, N. Ranger, S. Hallegatte, J. Corfee-Morlot, C. Herweijer, and J. Chateau, 2011: A global ranking of port cities with high exposure to climate extremes. *Climatic Change*, **104(1)**, 89-111.

Haque, A.N., S. Grafakos, and M. Huijsman, 2012: Participatory integrated assessment of flood protection measures for climate adaptation in Dhaka. *Environment and Urbanization*, **24(1)**, 197-213.

Hardoy, J. and G. Pandiella, 2007: Adaptación de las ciudades Argentinas a los efectos del cambio y la variabilidad climática. *Medio Ambiente y Urbanización*, **67(1)**, 45-58.

Hardoy, J. and G. Pandiella, 2009: Urban poverty and vulnerability to climate change in Latin America. *Environment and Urbanization*, **21(1)**, 203-224.

Hardoy, J. and P. Romero-Lankao, 2011: Latin American cities and climate change: challenges and options to mitigation and adaptation responses. *Current Opinion in Environmental Sustainability*, **3(3)**, 158-163.

Hardoy, J. and R. Ruete, 2013: Incorporating climate change adaptation into planning for a liveable city in Rosario, Argentina. *Environment and Urbanization*, **25(2)**, 339-360.

Hardoy, J. and L.S. Velásquez Barrero, 2013: Re-thinking 'Biomanizales' to address climate change adaptation in Manizales, Colombia. *Environment and Urbanization* (in press).

Hardoy, J.E., D. Mitlin, and D. Satterthwaite, 2001: *Environmental Problems in an Urbanizing World.* Earthscan, London, UK and New York, NY, USA, 464 pp.

Hardoy, J., G. Pandiella, and L.S. Velásquez Barrero, 2011: Local disaster risk reduction in Latin American urban areas. *Environment and Urbanization*, **23(2)**, 401-413.

Harlan, S.L. and D.M. Ruddell, 2011: Climate change and health in cities: impacts of heat and air pollution and potential co-benefits from mitigation and adaptation. *Current Opinion in Environmental Sustainability*, **3(3)**, 126-134.

Hasan, A., 2006: Orangi Pilot Project: the expansion of work beyond Orangi and the mapping of informal settlements and infrastructure. *Environment and Urbanization*, **18(2)**, 451-480.

Hasan, A., M. Younus, and S.A. Zaidi, 2002: *Understanding Karachi: Planning and Reform for the Future.* 2nd edn., City Press, Karachi, Pakistan, 171 pp.

Haughton, G., 1999: Information and participation within environmental management. *Environment and Urbanization*, **11(2)**, 51-62.

Hayhoe, K., M. Robson, J. Rogula, M. Auffhammer, N. Miller, J. VanDorn, and D. Wuebbles, 2010: An integrated framework for quantifying and valuing climate change impacts on urban energy and infrastructure: a Chicago case study. *Journal of Great Lakes Research*, **36(Supple 2)**, 94-105.

He, J., J. Liu, D. Zhuang, W. Zhang, and M. Liu, 2007: Assessing the effect of land use/land cover change on the change of urban heat island intensity. *Theoretical and Applied Climatology*, **90(3)**, 217-226.

Healey, P., 2006: *Collaborative Planning: Shaping Places in Fragmented Societies.* 2nd edn., Palgrave Macmillan, New York, NY, USA, 366 pp.

Hebert, K. and R. Taplin, 2006: Climate change impacts and coastal planning in the Sydney greater metropolitan region. *Australian Planner*, **43(3)**, 34-41.

Hedger, M., 2011: *Climate Finance in Bangladesh: Lessons for Development Co-operation and Climate Finance at National Level.* EDC2020 Policy Brief No. 14, European Development Co-operation to 2020 (EDC2020) Consortium Project, European Association of Development Research and Training Institutes (EADI), Bonn, Germany, 4 pp.

Hedger, M. and N. Bird, 2011: *Climate Change Challenges for European Development Corporation: Issues towards 2020*. EDC2020 Policy Brief No. 15, European Development Co-operation to 2020 (EDC2020) Consortium Project, European Association of Development Research and Training Institutes (EADI), Bonn, Germany, 4 pp.

Hedger, M., T. Mitchell, J. Leavy, M. Greeley, A. Downie, and L. Horrocks, 2008: *Desk Review: Evaluation of Adaptation to Climate Change from a Development Perspective.* Commissioned by Global Environment Facility (GEF) and Financed by the Department for International Development (DFID) for the GEF Evaluation Office International Conference on Evaluating Climate Change and Development, Alexandria, May 10 – 13, 2008, Institute of Development Studies (IDS), Sussex, UK, 60 pp.

Helsinki Region Environmental Services Authority, 2012: *Helsinki Metropolitan Area Climate Change Adaptation Strategy*. Helsinki, Finland, 30 pp.

Herrfahrdt-Pähle, E., 2010: South African water governance between administrative and hydrological boundaries. *Climate and Development*, **2(2)**, 111-127.

Hoa, D.T.M., D.A. Nguyet, N.H. Phuong, D.T. Phuong, V.T. Nga, R. Few, and A. Winkels, 2013: *Heat Stress and Adaptive Capacity of Low-Income Outdoor Workers and their Families in the City of Da Nang, Vietnam*. ACCCRN Working Paper Series 3: 2013, Asian Cities Climate Change Resilience Network (ACCCRN) Initiative, International Institute for Environment and Development (IIED), London, UK, 86 pp.

Hodo-Abalo, S., M. Banna, and B. Zeghmati, 2012: Performance analysis of a planted roof as a passive cooling technique in hot-humid tropics. *Renewable Energy*, **39(1)**, 140-148.

Holt, T. and J. Pullen, 2007: Urban canopy modeling of the New York City metropolitan area: a comparison and validation of single-and multilayer parameterizations. *Monthly Weather Review*, **135(5)**, 1906-1930.

Holt, T., J. Pullen, and C.H. Bishop, 2009: Urban and ocean ensembles for improved meteorological and dispersion modelling of the coastal zone. *Tellus A*, **61(2)**, 232-249.

Hoornweg, D. and P. Bhada-Tata, 2012: *What a Waste: A Global Review of Solid Waste Management*. Urban Development Series, Knowledge Paper No. 15, World Bank, Washington, DC, USA, 98 pp.

Hoornweg, D., L. Sugar, and C.L. Trejos Gómez, 2011: Cities and greenhouse gas emissions: moving forward. *Environment and Urbanization*, **23(1)**, 207-227.

Houtzager, P.P. and A.K. Acharya, 2011: Associations, active citizenship, and the quality of democracy in Brazil and Mexico. *Theory and Society*, **40(1)**, 1-36.

Howard, G., K. Charles, K. Pond, A. Brookshaw, R. Hossain, and J. Bartram, 2010: Securing 2020 vision for 2030: climate change and ensuring resilience in water and sanitation services. *Journal of Water and Climate Change*, **1(1)**, 2-16.

Huang, C., P. Vaneckova, X. Wang, G. FitzGerald, Y. Guo, and S. Tong, 2011: Constraints and barriers to public health adaptation to climate change: a review of the literature. *American Journal of Preventive Medicine*, **40(2)**, 183-190.

Hunt, A. and P. Watkiss, 2011: Climate change impacts and adaptation in cities: a review of the literature. *Climatic Change*, **104(1)**, 13-49.

Iamarino, M., S. Beevers, and C. Grimmond, 2012: High-resolution (space, time) anthropogenic heat emissions: London 1970-2025. *International Journal of Climatology*, **32(11)**, 1754-1767.

Ichinose, T., K. Shimodozono, and K. Hanaki, 1999: Impact of anthropogenic heat on urban climate in Tokyo. *Atmospheric Environment*, **33(24)**, 3897-3909.

ICLEI, 2010: *Changing Climate, Changing Communities: Guide and Workbook for Municipal Climate Adaptation*. International Council for Local Environmental Initiatives (ICLEI) – Local Governments for Sustainability- Canada (ICLEI-Canada), Toronto, Ontario, Canada, 75 pp.

ICLEI, 2011: *Financing the Resilient City: A Demand Driven Approach to Development, Disaster Risk Reduction and Climate Adaptation*. An ICLEI White Paper, ICLEI Global Report, International Council for Local Environmental Initiatives (ICLEI) – Local Governments for Sustainability, ICLEI World Secretariat, Bonn, Germany, 47 pp.

ICLEI Oceania, 2008: *Local Government Climate Change Adaptation Toolkit*. Cities for Climate Protection (CCP) Australia Adaptation Initiative, ICLEI Oceania, Melbourne, Australia, 61 pp.

IFRC, 2010: *World Disasters Report 2010: Focus on Urban Risk.* International Federation of Red Cross and Red Crescent Societies (IFRC), Geneva, Switzerland, 211 pp.

IFRC, 2011: *Key Determinants of a Successful CBDRR Programme*. International Federation of Red Cross and Red Crescent Societies (IFRC), Geneva, Switzerland, 146 pp.

Imparato, I. and J. Ruster, 2003: *Slum Upgrading and Participation: Lessons from Latin America.* World Bank Publications, Washington, DC, USA, 489 pp.

Institute for Sustainable Communities, 2010: *Promising Practices in Adaptation & Resilience. A Resource Guide for Local Leaders: Version 1.0.* Produced in Partnership with the Centre for Clean Air Policy (CCAP), Institute for Sustainable Communities (ISC), Montpelier, VT, USA, 98 pp.

IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., Qin, D., Manning, M., Chen, Z., M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 996 pp.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, Plattner, G.-K., S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp.

IPCC, 2013: Summary for policy makers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1-36 (in press).

Iqbal, M.J. and J. Quamar, 2011: Measuring temperature variability of five major cities of Pakistan. *Arabian Journal of Geosciences*, **4(3)**, 595-606.

Ismail, A., M.H.A. Samad, and A.M.A. Rahman, 2011: The investigation of green roof and white roof cooling potential on single storey residential building in the Malaysian climate. *World Academy of Science, Engineering and Technology*, **52**, 129-137.

Jabeen, H., C. Johnson, and A. Allen, 2010: Built-in resilience: learning from grassroots coping strategies for climate variability. *Environment and Urbanization*, **22(2)**, 415-431.

Jackson, T.L., J.J. Feddema, K.W. Oleson, G.B. Bonan, and J.T. Bauer, 2010: Parameterization of urban characteristics for global climate modeling. *Annals of the Association of American Geographers*, **100(4)**, 848-865.

Jacob, D.J. and D.A. Winner, 2009: Effect of climate change on air quality. *Atmospheric Environment*, **43(1)**, 51-63.

Jacobs, K. and S. Williams, 2011: What to do now? Tensions and dilemmas in responding to natural disasters: a study of three Australian state housing authorities. *International Journal of Housing Policy*, **11(2)**, 175-193.

Jacob, K., R. Blake, R. Horton, D. Bader, and M. O'Grady, 2010: Chapter 7: Indicators and monitoring. *Annals of the New York Academy of Sciences*, **1196(1)**, 127-142.

Jacob, K., G. Deodatis, J. Atlas, M. Whitcomb, M. Lopeman, O. Markogiannaki, Z. Kennett, A. Morla, R. Leichenko, and P. Ventura, 2011: Transportation. In: *Responding to Climate Change in New York State: The ClimAID Integrated Assessment for Effective Climate Change Adaptation* [Rosenzweig, C., W. Solecki, A. DeGaetano, M. O'Grady, S. Hassol, and P. Grabhorn (eds.)]. Technical Report, NYSERDA Final Report No. 11-18, New York State Energy Research and Development Authority (NYSERDA), Albany, NY, USA, pp. 299-362.

Jaroszweski, D., L. Chapman, and J. Petts, 2010: Assessing the potential impact of climate change on transportation: the need for an interdisciplinary approach. *Journal of Transport Geography*, **18(2)**, 331-335.

Jasanoff, S., 1998: *The Fifth Branch: Science Advisers as Policymakers.* Harvard University Press, Cambridge, MA, USA, 320 pp.

Jha, A.K., R. Bloch, and J. Lamond, 2012: *Cities and Flooding: A Guide to Integrated Urban Flood Risk Management for the 21st Century.* World Bank Publications, Washington, DC, USA, 632 pp.

Jim, C., 2012: Effect of vegetation biomass structure on thermal performance of tropical green roof. *Landscape and Ecological Engineering*, **8(2)**, 173-187.

Jo, J.H., J. Carlson, J.S. Golden, and H. Bryan, 2010: Sustainable urban energy: development of a mesoscale assessment model for solar reflective roof technologies. *Energy Policy*, **38(12)**, 7951-7959.

Johannsen, J., L. Tejerina, and A. Glassman, 2009: *Conditional Cash Transfers in Latin America: Problems and Opportunities.* Inter-American Development Bank Social Protection and Health Division, Inter-American Development Bank, Washington, DC, USA, 35 pp.

Johansson, T.B., N. Nakicenovic, A. Patwardhan, and L. and Gomez-Echeverri (eds.), 2012: *Global Energy Assessment: Toward a Sustainable Future*. Cambridge University Press, Cambridge, UK, 1865 pp.

Johnson, C., 2011: *Creating an Enabling Environment for Reducing Disaster Risk: Recent Experience of Regulatory Frameworks for Land, Planning and Building in Low and Middle-Income Countries.* Background Paper for the Global Assessment Report on Disaster Risk Reduction 2011 (GAR 2011), United Nations Office for Disaster Risk Reduction (UNISDR), Geneva, Switzerland, 43 pp.

Johnson, C. and S. Blackburn, 2013: Advocacy for urban resilience: UNISDR's Making Cities Resilient Campaign. *Environment and Urbanization* (in press).

Jollands, N., M. Ruth, C. Bernier, and N. Golubiewski, 2007: The climate's long-term impact on New Zealand infrastructure (CLINZI) project – a case study of Hamilton City, New Zealand. *Journal of Environmental Management*, **83(4)**, 460-477.

Juhola, S. and L. Westerhoff, 2011: Challenges of adaptation to climate change across multiple scales: a case study of network governance in two European countries. *Environmental Science & Policy*, **14(3)**, 239-247.

Jung, S., 2008: Spatial variability in long-term changes of climate and oceanographic conditions in Korea. *Journal of Environmental Biology*, **29(4)**, 519-529.

Kalnay, E., M. Cai, H. Li, and J. Tobin, 2006: Estimation of the impact of land-surface forcings on temperature trends in eastern United States. *Journal of Geophysical Research*, **111(D6)**, D06106, doi:10.1029/2005JD006555.

Katragkou, E., P. Zanis, I. Kioutsioukis, I. Tegoulias, D. Melas, B. Krüger, and E. Coppola, 2011: Future climate change impacts on summer surface ozone from regional climate-air quality simulations over Europe. *Journal of Geophysical Research: Atmospheres (1984–2012)*, **116(D22)**, doi:10.1029/2011JD015899.

Kazmierczak, A. and J. Carter, 2010: *Adaptation to Climate Change Using Green and Blue Infrastructure: A Database of Case Studies.* University of Manchester, Manchester, UK, 172 pp.

Kehew, R., 2009: Projecting globally, planning locally: a progress report from cities in developing countries. In: *Climate Sense* [World Meteorological Organization (ed.)]. Tudor Rose, Leicester, UK, pp. 161-164.

Kehew, R., M. Kolisa, C. Rollo, A. Callejas, and G. Alber, 2012: Urban climate governance in the Philippines, Mexico and South Africa: national-and state-level laws and policies. In: *Resilient Cities 2: Cities and Adaptation to Climate Change – Proceedings of the Global Forum 2011* [Otto-Zimmermann, K. (ed.)]. Springer, Dordrecht, Netherlands, pp. 305-315.

Kehew, R.B., M. Kolisa, C. Rollo, A. Callejas, G. Alber, and L. Ricci, 2013: Formulating and implementing climate change laws and policies in the Philippines, Mexico (Chiapas), and South Africa: a local government perspective. *Local Environment*, **18(6)**, 723-737.

Keim, M.E., 2008: Building human resilience: the role of public health preparedness and response as an adaptation to climate change. *American Journal of Preventive Medicine*, **35(5)**, 508-516.

Kellett, J. and A. Sparks, 2012: *Disaster Risk Reduction: Spending Where It Should Count.* Briefing Paper, Global Humanitarian Assistance, Somerset, UK, 36 pp.

Kennedy, C. and J. Corfee-Morlot, 2013: Past performance and future needs for low carbon climate resilient infrastructure – an investment perspective. *Energy Policy*, **59**, 773-783.

Kennedy, C., S. Pincetl, and P. Bunje, 2011: The study of urban metabolism and its applications to urban planning and design. *Environmental Pollution*, **159(8)**, 1965-1973.

Keogh, B., J. Westbrook, and O. Suess, 2011: The trouble with catastrophe bonds. *Bloomberg Businessweek Magazine*, (25 April 2011), www.businessweek.com/magazine/content/11_18/b4226055260651.htm.

Kern, K. and A. Gotelind, 2009: Governing climate change in cities: modes of urban climate governance in multilevel systems. In: *Competitive Cities and Climate Change*. OECD Conference Proceedings, 9 – 10 October 2008, Milan, Italy, OECD, Paris, France, pp. 171-196.

Kessler, R., 2011: Stormwater strategies: cities prepare aging infrastructure for climate change. *Environmental Health Perspectives*, **119(12)**, a514-a519.

Khan, F., D. Mustafa, D. Kull, and The Risk Resilience Team, 2008: *Evaluating the Costs and Benefits of Disaster Risk Reduction under Changing Climatic Conditions: Pakistan Case Study. From Risk to Resilience, Working Paper No. 7* [Moench, M., E. Caspari, and A. Pokh (eds.)]. ProVention Consortium, Institute for Social and Environmental Transition (ISET), and ISET-Nepal, Kathmandu, Nepal, 24 pp.

Khattri, A., D. Parameshwar, and S. Pellech, 2010: *Opportunities for Private Sector Engagement in Urban Climate Change Resilience Building*. Intellecap, Asian Cities Climate Change Resilience Network (ACCCRN), and the Rockefeller Foundation, Bangkok, Thailand, 94 pp.

Kienberger, S., T. Blaschke, and R.Z. Zaidi, 2013: A framework for spatio-temporal scales and concepts from different disciplines: the 'vulnerability cube'. *Natural Hazards*, **68(3)**, 1343-1369.

Kinney, P.L., 2008: Climate change, air quality, and human health. *American Journal of Preventive Medicine*, **35(5)**, 459-467.

Kirshen, P., M. Ruth, and W. Anderson, 2008: Interdependencies of urban climate change impacts and adaptation strategies: a case study of Metropolitan Boston USA. *Climatic Change*, **86(1)**, 105-122.

Kithiia, J., 2010: Old notion–new relevance: setting the stage for the use of social capital resource in adapting East African coastal cities to climate change. *International Journal of Urban Sustainable Development*, **1(1-2)**, 17-32.

Kithiia, J., 2011: Climate change risk responses in East African cities: need, barriers and opportunities. *Current Opinion in Environmental Sustainability*, **3(3)**, 176-180.

Kithiia, J. and R. Dowling, 2010: An integrated city-level planning process to address impacts of climate change in Kenya: the case of Mombasa. *Cities*, **27(6)**, 466-475.

Kithiia, J. and A. Lyth, 2011: Urban wildscapes and green spaces in Mombasa and their potential contribution to climate change adaptation and mitigation. *Environment and Urbanization*, **23(1)**, 251-265.

Kiunsi, R., 2013: The constraints on climate change adaptation in a city with a large development deficit: the case of Dar es Salaam. *Environment and Urbanization*, **25(2)**, 321-337.

Koetse, M.J. and P. Rietveld, 2009: The impact of climate change and weather on transport: an overview of empirical findings. *Transportation Research Part D: Transport and Environment*, **14(3)**, 205-221.

Kolokotroni, M., M. Davies, B. Croxford, S. Bhuiyan, and A. Mavrogianni, 2010: A validated methodology for the prediction of heating and cooling energy demand for buildings within the Urban Heat Island: case-study of London. *Solar Energy*, **84(12)**, 2246-2255.

Komori, D., S. Nakamura, M. Kiguchi, A. Nishijima, D. Yamazaki, S. Suzuki, A. Kawasaki, K. Oki, and T. Oki, 2012: Characteristics of the 2011 Chao Phraya River flood in Central Thailand. *Hydrological Research Letters*, **6**, 41-46.

Kousky, C. and S.H. Schneider, 2003: Global climate policy: will cities lead the way? *Climate Policy*, **3(4)**, 359-372.

Kovats, S. and R. Akhtar, 2008: Climate, climate change and human health in Asian cities. *Environment and Urbanization*, **20(1)**, 165-175.

Krishnamurthy, P.K., J.B. Fisher, and C. Johnson, 2011: Mainstreaming local perceptions of hurricane risk into policymaking: a case study of community GIS in Mexico. *Global Environmental Change*, **21(1)**, 143-153.

La Greca, P., D. La Rosa, F. Martinico, and R. Privitera, 2011: Agricultural and green infrastructures: the role of non-urbanised areas for eco-sustainable planning in a metropolitan region. *Environmental Pollution*, **159(8)**, 2193-2202.

Lam, Y., J. Fu, S. Wu, and L. Mickley, 2011: Impacts of future climate change and effects of biogenic emissions on surface ozone and particulate matter concentrations in the United States. *Atmospheric Chemistry and Physics*, **11(10)**, 4789-4806.

Lamhauge, N., E. Lanzi, and S. Agrawala, 2012: *Monitoring and Evaluation for Adaptation: Lessons from Development Co-operation Agencies.* OECD Environment Working Paper No. 38, OECD Publishing, Paris, France, 49 pp.

Larsen, P.H., S. Goldsmith, O. Smith, M.L. Wilson, K. Strzepek, P. Chinowsky, and B. Saylor, 2008: Estimating future costs for Alaska public infrastructure at risk from climate change. *Global Environmental Change*, **18(3)**, 442-457.

Laube, W. and N. van de Giesen, 2006: Ghanaian water law and policy: institutional and hydrological perspectives. In: *Hydrological Information in Water Law and Policy: Current Practices and Future Potential* [Wallace, J., P. Wouters, and S. Pazvakavambwa (eds.)]. Water Policy Series, Kluwer, Dordrecht, Netherlands.

Laurent, S., 2010: Xynthia: une communication qui passe mal. *Le Monde* (April 19 edn.), Paris, France, www.lemonde.fr/politique/article/2010/04/19/xynthia-une-communication-qui-passe-mal_1337353_823448.html.

Lee-Smith, D., 2010: Cities feeding people: an update on urban agriculture in equatorial Africa. *Environment and Urbanization*, **22(2)**, 483-499.

Leichenko, R., 2011: Climate change and urban resilience. *Current Opinion in Environmental Sustainability*, **3(3)**, 164-168.

Leiserowitz, A., 2006: Climate change risk perception and policy preferences: the role of affect, imagery, and values. *Climatic Change*, **77(1)**, 45-72.

Lemonsu, A., R. Kounkou-Arnaud, J. Desplat, J. Salagnac, and V. Masson, 2013: evolution of the Parisian urban climate under a global changing climate. *Climatic Change*, **116(3-4)**, 679-692.

Levina, E., J. Jacob, L.E.R. Bustillos, and I. Ortiz, 2007: *Policy frameworks for Adaptation to Climate Change in Coastal Zones: The Case of the Gulf of Mexico.* COM/ENV/EPOC/IEA/SLT(2007)2, OECD Publishing, Paris, France, 68 pp.

Levy, C., 2013: Travel choice reframed: "deep distribution" and gender in urban transport. *Environment and Urbanization*, **25(1)**, 47-63.

Li, B., 2013: Governing urban climate change adaptation in China. *Environment and Urbanization*, **25(2)**, 413-427.

Liberatore, A. and S. Funtowicz, 2003: 'Democratising'expertise, 'expertising' democracy: what does this mean, and why bother? *Science and Public Policy*, **30(3)**, 146-150.

Lim, B., E. Spanger-Siegfried, I. Burton, E. Malone, and S. Huq, 2004: *Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies, and Measures.* Cambridge University Press, Cambridge, UK, 268 pp.

Lindgren, J., D.K. Jonsson, and A. Carlsson-Kanyama, 2009: Climate adaptation of railways: lessons from Sweden. *European Journal of Transport and Infrastructure Research*, **9(2)**, 164-181.

Lindseth, G., 2004: The Cities for Climate Protection Campaign (CCPC) and the framing of local climate policy. *Local Environment*, **9(4)**, 325-336.

Linnekamp, F., A. Koedam, and I.S.A. Baud, 2011: Household vulnerability to climate change: examining perceptions of households of flood risks in Georgetown and Paramaribo. *Habitat International*, **35(3)**, 447-456.

Liu, J. and X. Deng, 2011: Impacts and mitigation of climate change on Chinese cities. *Current Opinion in Environmental Sustainability*, **3(3)**, 188-192.

Livengood, A. and K. Kunte, 2012: Enabling participatory planning with GIS: a case study of settlement mapping in Cuttack, India. *Environment and Urbanization*, **24(1)**, 77-97.

Love, G., A. Soares, and H. Püempel, 2010: Climate change, climate variability and transportation. *Procedia Environmental Sciences*, **1**, 130-145.

Lowe, A., J. Foster, and S. Winkelman, 2009: *Ask the Climate Question: Adapting to Climate Change Impacts in Urban Regions.* Center for Clean Air Policy (CCAP), Washington, DC, USA, 41 pp.

Luino, F. and D. Castaldini eds., 2011: Special Issue of NHESS: Geo-Hydrological Risk and Town and Country Planning. *Natural Hazards and Earth System Sciences*, **(115)**, 1253-2346, www.nat-hazards-earth-syst-sci.net/special_issue115.html.

Luque, A., G.A.S. Edwards, and C. Lalande, 2013: The local governance of climate change: new tools to respond to old limitations in Esmeraldas, Ecuador. *Local Environment*, **18(6)**, 738-751.

Lwasa, S., 2010: Adapting urban areas in Africa to climate change: the case of Kampala. *Current Opinion in Environmental Sustainability*, **2(3)**, 166-171.

Lyons, M., 2009: Building back better: the large-scale impact of small-scale approaches to reconstruction. *World Development*, **37(2)**, 385-398.

Major, D., A. Omojola, M. Dettinger, R. Hanson, and R. Sanchez-Rodriguez, 2011: Climate change, water, and wastewater in cities. In: *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, C., W.D. Solecki, S.A. Hammer, and S. Mehrotra (eds.)]. Cambridge University Press, Cambridge, UK, pp. 113-143.

Maller, C.J. and Y. Strengers, 2011: Housing, heat stress and health in a changing climate: promoting the adaptive capacity of vulnerable households, a suggested way forward. *Health Promotion International*, **26(4)**, 492-498.

Manda, M.A.Z., 2007: Mchenga – urban poor housing fund in Malawi. *Environment and Urbanization*, **19(2)**, 337-359.

Mansilla, E., A. Brenes, and J. and Icaza, 2008: *Centroamérica a 10 Años de Mitch. Reflexiones en Torno a la Reducción del Riesgo*. Centro de Coordinación para la Prevención de los Desastres Naturales en América Central (CEPREDENAC) and the World Bank, Washington, DC, USA, 81 pp.

Manton, M.J., 2010: Trends in climate extremes affecting human settlements. *Current Opinion in Environmental Sustainability*, **2(3)**, 151-155.

Manuel-Navarrete, D., M. Pelling, and M. Redclift, 2011: Critical adaptation to hurricanes in the Mexican Caribbean: development visions, governance structures, and coping strategies. *Global Environmental Change*, **21(1)**, 249-258.

Manyena, S.B., 2006: The concept of resilience revisited. *Disasters*, **30(4)**, 434-450.

Manyena, S., G. O'Brien, P. O'Keefe, and J. Rose, 2011: Disaster resilience: a bounce back or bounce forward ability? *Local Environment*, **16(5)**, 417-424.

Martins, R.D. and L. da Costa Ferreira, 2011: Climate change action at the city level: tales from two megacities in Brazil. *Management of Environmental Quality: An International Journal*, **22(3)**, 344-357.

Massetti, E., S. Pinton, and D. Zanoni, 2007: National through to local climate policy in Italy. *Environmental Sciences*, **4(3)**, 149-158.

Mathey, J., S. Rößler, I. Lehmann, and A. Bräuer, 2011: Urban green spaces: potentials and constraints for urban adaptation to climate change. In: *Resilient Cities: Cities and Adaptation to Climate Change – Proceedings of the Global Forum 2010* [Otto-Zimmermann, K. (ed.)]. Springer, Dordrecht, Netherlands, pp. 479-485.

Matzarakis, A. and C. Endler, 2010: Climate change and thermal bioclimate in cities: impacts and options for adaptation in Freiburg, Germany. *International Journal of Biometeorology*, **54(4)**, 479-483.

May, P., F.V. Neto, V. Denardin, and W. Loureiro, 2002: Using fiscal instruments to encourage conservation: municipal responses to the 'ecological' value added tax in Paraná and Minas Gerais, Brazil. In: *Selling Forest Environmental Services: Market-based Mechanisms for Conservation and Development* [Pagiola, S., J. Bishop, and N. Landell-Mills (eds.)]. Earthscan, Abingdon, Oxon, UK and New York, NY, USA, pp. 173-200.

McBain, W., D. Wilkes, and M. Retter, 2010: *Flood Resilience and Resistance for Critical Infrastructure.* CIRIA C688, CIRIA Project RP913, CIRIA, London, UK, 112 pp.

McCarney, P.L., 2012: City Indicators on climate change implications for governance. *Environment and Urbanization Asia*, **3(1)**, 1-39.

McCarney, P., H. Blanco, J. Carmin, and M. and Colley, 2011: Cities and climate change: the challenges for governance. In: *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, C., W.D. Solecki, S.A. Hammer, and S. and Mehrotra (eds.)]. Cambridge University Press, Cambridge, UK, pp. 249-269.

McCarthy, M.P., M.J. Best, and R.A. Betts, 2010: Climate change in cities due to global warming and urban effects. *Geophysical Research Letters*, **37(9)**, L09705, doi:10.1029/2010GL042845.

McCarthy, M., C. Harpham, C. Goodess, and P. Jones, 2011: Simulating climate change in UK cities using a regional climate model, HadRM3. *International Journal of Climatology*, **32(12)**, 1875-1888.

McDonald, R.I., P. Green, D. Balk, B.M. Fekete, C. Revenga, M. Todd, and M. Montgomery, 2011: Urban growth, climate change, and freshwater availability. *Proceedings of the National Academy of Sciences of the United States of America*, **108(15)**, 6312-6317.

McFarlane, C., 2008: Sanitation in Mumbai's informal settlements: state, 'slum' and infrastructure. *Environment and Planning A*, **40(1)**, 88-107.

McGranahan, G., 2007: *Urban Environments*, *Wealth and Health: Shifting Burdens and Possible Responses in Low and Middle-Income Nations.* Human Settlements Working Paper, Urban Environments No. 1, International Institute for Environment and Development (IIED), London, UK, 53 pp.

McGranahan, G., D. Balk, and B. Anderson, 2007: The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization*, **19(1)**, 17-37.

McMichael, A., S. Friel, A. Nyong, and C. Corvalan, 2008: Global environmental change and health: impacts, inequalities, and the health sector. *BMJ* (formerly the *British Medical Journal*), **336(7637)**, 191.

Mdluli, T.N. and C.H. Vogel, 2010: Challenges to achieving a successful transition to a low carbon economy in South Africa: examples from poor urban communities. *Mitigation and Adaptation Strategies for Global Change*, **15(3)**, 205-222.

Measham, T.G., B.L. Preston, T.F. Smith, C. Brooke, R. Gorddard, G. Withycombe, and C. Morrison, 2011: Adapting to climate change through local municipal planning: barriers and challenges. *Mitigation and Adaptation Strategies for Global Change*, **16(8)**, 889-909.

Medina, M., 2007: *The World's Scavengers: Salvaging for Sustainable Consumption and Production.* AltaMira Press, Lanham, MD, USA, 318 pp.

Mees, H.P. and P.P. Driessen, 2011: Adaptation to climate change in urban areas: climate-greening London, Rotterdam, and Toronto. *Climate Law*, **2(2)**, 251-280.

Mehrotra, S., C.E. Natenzon, A. Omojola, R. Folorunsho, J. Gilbride, and C. Rosenzweig, 2009: Framework for city climate risk assessment. In: *Proceedings of Fifth Urban Research Symposium: Cities and Climate Change – Responding to the Urgent Agenda, 28 – 30 June 2009, Marseilles, France*. World Bank, Washington, DC, USA, uccrn.org/documents/Framework_for_City_Risk_Assessment-June17.pdf.

Mehrotra, S., C. Rosenzweig, W. Solecki, C. Natenzon, A. Omojola, R. Folorunsho, and J. Gillbride, 2011a: Cities, disasters and climate risk. In: *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, C., W.D. Solecki, S.A. Hammer, and S. Mehrotra (eds.)]. Cambridge University Press, Cambridge, UK, pp. 15-42.

Mehrotra, S., B. Lefevre, R. Zimmerman, K. Gercek, S. Jacob, and S. Srinivasan, 2011b: Climate change and urban transport systems. In: *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, C., W.D. Solecki, S.A. Hammer, and S. Mehrotra (eds.)]. Cambridge University Press, Cambridge, UK, pp. 145-177.

Merk, O., S. Saussier, C. Staropoli, E. Slack, and J. Kim, 2012: *Financing Green Urban Infrastructure.* OECD Regional Development Working Paper 2012/10, OECD Publishing, Paris, France, 65 pp.

Mideksa, T.K. and S. Kallbekken, 2010: The impact of climate change on the electricity market: a review. *Energy Policy*, **38(7)**, 3579-3585.

Mills, E., 2007: Synergisms between climate change mitigation and adaptation: an insurance perspective. *Mitigation and Adaptation Strategies for Global Change*, **12(5)**, 809-842.

Mills, E., 2012: The greening of insurance. *Science*, **338(6113)**, 1424-1425.

Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. ettenmaier, and R.J. Stouffer, 2008: Stationarity is dead: whither water management? *Science*, **319(5863)**, 573-574.

Milman, A. and A. Short, 2008: Incorporating resilience into sustainability indicators: an example for the urban water sector. *Global Environmental Change*, **18(4)**, 758-767.

Mirasgedis, S., Y. Sarafidis, E. Georgopoulou, V. Kotroni, K. Lagouvardos, and D. Lalas, 2007: Modeling framework for estimating impacts of climate change on electricity demand at regional level: case of Greece. *Energy Conversion and Management*, **48(5)**, 1737-1750.

Mitchell, T., M. Van Aalst, and P.S. Villanueva, 2010: *Assessing Progress on Integrating Disaster Risk Reduction and Climate Change Adaptation in Development Processes.* Strengthening Climate Resilience Discussion Paper 2, Institute of Development Studies (IDS), Sussex, UK, 28 pp.

Mitlin, D., 2008: With and beyond the state – co-production as a route to political influence, power and transformation for grassroots organizations. *Environment and Urbanization*, **20(2)**, 339-360.

Mitlin, D., 2012: Lessons from the urban poor: collective action and the rethinking of development. In: *Climate Change and the Crisis of Capitalism: A Chance to Reclaim, Self, Society and Nature* [Pelling, M., D. Manuel-Navarrete, and M. Redclift (eds.)]. Routledge, Abingdon, Oxon, UK and New York, NY, USA , pp. 85-98.

Mitlin, D. and D. Satterthwaite, 2013: *Urban Poverty in the Global South: Scale and Nature.* Routledge, Abingdon, Oxon, UK and New York, NY, USA, 354 pp.

Moench, M., S. Tyler, and J. Lage, 2011: *Catalyzing Urban Climate Resilience: Applying Resilience Concepts to Planning Practice in the ACCCRN Program (2009-2011)*. Institute for Social and Environmental Transition, International (ISET-International), Boulder, CO, USA, 292 pp.

Mohan, G. and K. Stokke, 2000: Participatory development and empowerment: the dangers of localism. *Third World Quarterly*, **21(2)**, 247-268.

Mohan, M., A. Kandya, and A. Battiprolu, 2011a: Urban heat island effect over national capital region of India: a study using the temperature trends. *Journal of Environmental Protection*, **2(4)**, 465-472.

Mohan, M., S.K. Pathan, K. Narendrareddy, A. Kandya, and S. Pandey, 2011b: dynamics of urbanization and its impact on land-use/land-cover: a case study of megacity Delhi. *Journal of Environmental Protection*, **2(9)**, 1274-1283.

Mohan, M., Y. Kikegawa, B. Gurjar, S. Bhati, A. Kandya, and K. Ogawa, 2012: Urban heat island assessment for a tropical urban airshed in India. *Atmospheric and Climate Sciences*, **2(2)**, 127-138.

Montgomery, M.R., R. Stren, B. Cohen, and H.E. Reed, 2003: *Cities Transformed: Demographic Change and its Implications in the Developing World.* National Academies Press, Washington, DC, USA, 529 pp.

Moser, C. and D. Satterthwaite, 2009: Towards pro-poor adaptation to climate change in the urban centres of low- and middle-income countries. In: *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World* [Mearns, R. and A. Norton (eds.)]. World Bank, Washington, DC, USA, pp. 231-258.

Moser, S.C., 2006: Talk of the city: engaging urbanites on climate change. *Environmental Research Letters*, **1(1)**, 014006, doi:10.1088/1748-9326/1/1/014006.

Moser, S.C., 2009: *Good Morning, America! The Explosive U.S. Awakening to the Need for Adaptation*. National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center, Charleston, SC, USA, and California Energy Commission, Sacramento, CA, USA, 39 pp.

Moser, S.C. and L. Dilling (eds.), 2007: *Creating a Climate for Change: Communicating Climate Change and Facilitating Social Change*. Cambridge University Press, Cambridge, UK and New York, NY, USA, 549 pp.

Moser, S.C. and A.L. Luers, 2008: Managing climate risks in California: the need to engage resource managers for successful adaptation to change. *Climatic Change*, **87**, 309-322.

Moser, S.C. and J. Tribbia, 2006: Vulnerability to inundation and climate change impacts in California: coastal managers' attitudes and perceptions. *Marine Technology Society Journal*, **40(4)**, 35-44.

Moser, C., A. Norton, A. Stein, and S. Georgieva, 2010: *Pro-Poor Adaptation to Climate Change in Urban Centers: Case Studies of Vulnerability and Resilience in Kenya and Nicaragua*. The World Bank Sustainable Development Network, Social Development Department, Report No. 54947-GLB, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 84 pp.

Mukheibir, P., 2008: Water resources management strategies for adaptation to climate-induced impacts in South Africa. *Water Resources Management*, **22(9)**, 1259-1276.

Mukheibir, P. and G. Ziervogel, 2007: Developing a Municipal Adaptation Plan (MAP) for climate change: the city of Cape Town. *Environment and Urbanization*, **19(1)**, 143-158.

Muller, M., 2007: Adapting to climate change: water management for urban resilience. *Environment and Urbanization*, **19(1)**, 99-113.

Munich Re, 2004: *Megacities: Megarisks: Trends and Challenges for Insurance and Risk Management*. Münchener Rückversicherungs-Gesellschaf (Munich Re Group), Munich, Germany, 79 pp.

Nagendra, H. and D. Gopal, 2011: Tree diversity, distribution, history and change in urban parks: studies in Bangalore, India. *Urban Ecosystems*, **14(2)**, 211-223.

Nagy, G., M.G. Erache, and V. Fernández, 2007: El aumento del nivel del mar en la costa uruguaya del Río de la Plata. Tendencias, vulnerabilidades y medidas para la adaptación. *Medio Ambiente y Urbanización*, **67(1)**, 77-93.

National Research Council, 2007: *Analysis of Global Change Assessments: Lessons Learned.* National Academies Press, Washington, DC, USA, 196 pp.

National Research Council, 2008: *Public Participation in Environmental Assessment and Decision Making.* National Academies Press, Washington, DC, USA, 322 pp.

National Research Council, 2009: *Informing Decisions in a Changing Climate.* National Academies Press, Washington, DC, USA, 200 pp.

National Research Council, 2010: *Advancing the Science of Climate Change: America's Climate Choice*. National Academies Press, Washington, DC, USA, 528 pp.

Nelson, K.C., M.A. Palmer, J.E. Pizzuto, G.E. Moglen, P.L. Angermeier, R.H. Hilderbrand, M. Dettinger, and K. Hayhoe, 2008: Forecasting the combined effects of urbanization and climate change on stream ecosystems: from impacts to management options. *Journal of Applied Ecology*, **46(1)**, 154-163.

Newman, P., 2010: Green urbanism and its application to Singapore. *Environment and Urbanization Asia*, **1(2)**, 149-170.

Nicholls, R.J., 2004: Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios. *Global Environmental Change*, **14(1)**, 69-86.

Nie, L., O. Lindholm, G. Lindholm, and E. Syversen, 2009: Impacts of climate change on urban drainage systems – a case study in Fredrikstad, Norway. *Urban Water Journal*, **6(4)**, 323-332.

Niemi, E., M. Buckley, C. Neculae, and S. Reich, 2009a: *An Overview of Potential Economic Costs to Washington of a Business-As-Usual Approach to Climate Change*. A Report from the Program on Climate Economics, Climate Leadership Initiative, Institute for a Sustainable Environment, University of Oregon, Eugene, OR, USA, 47 pp.

Niemi, E., M. Buckley, C. Neculae, and S. Reich, 2009b: *An Overview of Potential Economic Costs to Oregon of a Business-As-Usual Approach to Climate Change*. A Report from the Program on Climate Economics, Climate Leadership Initiative, Institute for a Sustainable Environment, University of Oregon, Eugene, OR 47 pp.

Niemi, E., M. Buckley, C. Neculae, and S. Reich, 2009c: *An Overview of Potential Economic Costs to New Mexico of a Business-As-Usual Approach to Climate Change*. A Report from the Program on Climate Economics, Climate Leadership Initiative, Institute for a Sustainable Environment, University of Oregon, Eugene, OR, 46 pp.

Niño-Zarazúa, M., 2010: *Mexico's Progresa-Oportunidades and the Emergence of Social Assistance in Latin America.* BWPI Working Paper No. 142, Brooks World Poverty Institute, University of Manchester, Manchester, UK, 24 pp.

Nobre, C.A., A. Young, P. Saldiva, J.A. Marengo, A.D. Nobre, S. Alves Jr., G.C.M. Silva, and M. Lombardo, 2010: *Vulnerabilidade das Megacidades Brasileiras às Mudanças Climáticas: Regiao Metropolitana de Sao Paulo. Summário Executivo.* Centro de Ciência do Sistema Terrestre do Instituto Nacional de Pesquisas Espacia (CCST/INPE), Núcleo de Estudos de População da Universidade de Campina (NEPO/UNICAMP), Faculdade de Medicina da Universidade de São Paul (FM/USP), Instituto de Pesquisas Tecnológicas de São Paulo (IPT), Universidade Estadual de São Paulo (UNESP-Rio Claro), Sao Paulo, Brazil, 31 pp.

Norman, B., and H. Nakanishi, 2011: Planning for extreme weather events and climate change: innovative regional planning responses in Australia. In: *Proceedings of the 11th International Congress of Asian Planning Schools Association 19-21 September, University of Tokyo*, *Tokyo, Japan.* Secretariat for APSA2011, Tokyo, Japan, Paper No. E-1-1.

O'Hara, J.K. and K.P. Georgakakos, 2008: Quantifying the urban water supply impacts of climate change. *Water Resources Management*, **22(10)**, 1477-1497.

OECD, 2009: *Integrating Climate Change Adaptation into Development Cooperation: Policy Guidance*. Organisation for Economic Co-operation and Development (OECD), OECD Publishing, Paris, France, 190 pp.

OECD, 2010: *Cities and Climate Change*. OECD Publishing, Paris, France, 276 pp.

OECD, 2011: *Aid Effectiveness 2011: Progress in Implementing the Paris Declaration*. Organisation for Economic Co-operation and Development (OECD), OECD Publishing, Paris, France, 196 pp.

OECD, 2012: *Greening Development: Enhancing Capacity for Environmental Management and Governance*. Organisation for Economic Co-operation and Development (OECD), OECD Publishing, Paris, France, 100 pp., doi: 10.1787/9789264167896-en.

OECD, 2013: *Development Assistance Committee Statistics on Climate-Related Aid, On-line Creditor Reporting System Database.* Organisation for Economic Co-operation and Development (OECD), OECD, Paris, France, www.oecd.org/dac/stats/rioconventions.htm#data.

Oh, C.H. and R. Reuveny, 2010: Climatic natural disasters, political risk, and international trade. *Global Environmental Change*, **20(2)**, 243-254.

Ohashi, Y. and H. Kida, 2002: Local circulations developed in the vicinity of both coastal and inland urban areas: a numerical study with a mesoscale atmospheric model. *Journal of Applied Meteorology*, **41(1)**, 30-45.

Ojima, R., 2009: Perspectivas para a adaptação frente às mudanzas ambientais globais no contexto da urbanização brasileira: cenários para os estudos de população. In: *População e Mudança Climática: Dimensões Humanas das Mudanças Ambientais Globais* [Hogan, D. and E. Marandola Jr. (eds.)]. Uma publicação do Núcleo de Estudos de População (NEPO) e do Fundo de População das Nações Unidas (UNFPA), Núcleo de Estudos da População Universidade Estadual de Campinas (UNICAMP), Cidade Universitária Zeferino Vaz, Campinas, Brazil, pp. 11-24.

Olcina Cantos, J., M. Hernández Hernández, A.M. Rico Amorós, and E. Martínez Ibarra, 2010: Increased risk of flooding on the coast of Alicante (Region of Valencia, Spain). *Natural Hazards and Earth System Sciences*, **10(11)**, 2229-2234.

Oleson, K., 2012: Contrasts between urban and rural climate in CCSM4 CMIP5 climate change scenarios. *Journal of Climate*, **25(5)**, 1390-1412.

Oliveira, S., H. Andrade, and T. Vaz, 2011: The cooling effect of green spaces as a contribution to the mitigation of urban heat: a case study in Lisbon. *Building and Environment*, **46(11)**, 2186-2194.

Olsson, J., K. Berggren, M. Olofsson, and M. Viklander, 2009: Applying climate model precipitation scenarios for urban hydrological assessment: a case study in Kalmar City, Sweden. *Atmospheric Research*, **92(3)**, 364-375.

O'Neill, M.S. and K.L. Ebi, 2009: Temperature extremes and health: impacts of climate variability and change in the United States. *Journal of Occupational and Environmental Medicine*, **51(1)**, 13-25.

Onof, C. and K. Arnbjerg-Nielsen, 2009: Quantification of anticipated future changes in high resolution design rainfall for urban areas. *Atmospheric Research*, **92(3)**, 350-363.

Ostrom, E., 2009: *A Polycentric Approach for Coping with Climate Change.* Background Paper to the 2010 World Development Report, Policy Research Working Paper 5095, World Bank, Washington, DC, USA, 54 pp.

Oudin Åström, D., F. Bertil, and R. Joacim, 2011: Heat wave impact on morbidity and mortality in the elderly population: a review of recent studies. *Maturitas*, **69(2)**, 99-105.

Oven, K.J., S.E. Curtis, S. Reaney, M. Riva, M.G. Stewart, R. Ohlemüller, C.E. Dunn, S. Nodwell, L. Dominelli, and R. Holden, 2012: Climate change and health and social care: defining future hazard, vulnerability and risk for infrastructure systems supporting older people's health care in England. *Applied Geography*, **33**, 16-24.

Palin, E.J., H.E. Thornton, C.T. Mathison, R.E. McCarthy, R.T. Clark, and J. Dora, 2013: Future projections of temperature-related climate change impacts on the railway network of Great Britain. *Climatic Change*, **120(1-2)**, 71-93.

Palla, A., J. Sansalone, I. Gnecco, and L. Lanza, 2011: Storm water infiltration in a monitored green roof for hydrologic restoration. *Water Science and Technology*, **64(3)**, 766-773.

Parizotto, S. and R. Lamberts, 2011: Investigation of green roof thermal performance in temperate climate: a case study of an experimental building in Florianópolis city, Southern Brazil. *Energy and Buildings*, **43(7)**, 1712-1722.

Parnell, S. and R. Walawege, 2011: Sub-Saharan African urbanisation and global environmental change. *Global Environmental Change*, **21(Suppl. 1)**, S12-S20.

Parry, M.L., N. Arnell, P. Berry, D. Dodman, S. Fankhauser, C. Hope, S. Kovats, R. Nicholls, D. Satterthwaite, R. Tiffin, and T. Wheeler (eds.), 2009: *Assessing the Costs of Adaptation to Climate Change: A Review of the UNFCCC and Other Recent Estimates.* International Institute for Environment and Development (IIED) and the Grantham Institute for Climate Change, London, UK, 111 pp.

Patel, S. and C. Baptist, 2012: Editorial: Documenting by the undocumented. *Environment and Urbanization*, **24(1)**, 3-12.

Paulais, T. and J. Pigey, 2010: Adaptation and mitigation: what financing is available for local government investments in developing countries? In: *Cities and Climate Change: Responding to an Urgent Agenda* [Hoornweg, D., M. Freire, M.J. Lee, P. Bhada-Tata, and B. Yuen (eds.)]. World Bank, Washington, DC, USA, pp. 583-601.

Pavri, F., 2010: Urban expansion and sea-level rise related flood vulnerability for Mumbai (Bombay), India using remotely sensed data. In: *Geospatial Techniques in Urban Hazard and Disaster Analysis, Vol. 2* [Showalter, P.S. and Y. Lu (eds.)], Springer, Dordrecht, Netherlands, pp. 31-49.

Pelling, M., 2003: *The Vulnerability of Cities: Natural Disasters and Social Resilience.* Earthscan, Abingdon, Oxon, UK and New York, NY, USA, 212 pp.

Pelling, M., 2011a: *Adaptation to Climate Change: From Resilience to Transformation.* Routledge, Abingdon, Oxon, UK and New York, NY, USA, 203 pp.

Pelling, M., 2011b: Urban governance and disaster risk reduction in the Caribbean: the experiences of Oxfam GB. *Environment and Urbanization*, 23(2), 383-400.

Pelling, M. and K. Dill, 2010: Disaster politics: tipping points for change in the adaptation of sociopolitical regimes. *Progress in Human Geography*, **34(1)**, 21-37.

Pelling, M. and D. Manuel-Navarrete, 2011: From resilience to transformation: the adaptive cycle in two Mexican urban centers. *Ecology and Society*, **16(2)**, 11, www.ecologyandsociety.org/vol16/iss2/art11/.

Pelling, M. and B. Wisner, 2009: *Disaster Risk Reduction: Cases from Urban Africa.* Earthscan, Abingdon, Oxon, UK and New York, NY, USA, 224 pp.

Pelling, M. and Z. Zaidi, 2013: *Measuring Adaptive Capacity: Application of an Indexing Methodology in Guyana.* Working Paper No. 47, Environment, Politics, and Development Research Group, Department of Geography, King's College London, London, UK, 30 pp.

Pelling, M., D. Manuel-Navarrete, and M. Redclift (eds.), 2012: *Climate Change and the Crisis of Capitalism: A Chance to Reclaim, Self, Society and Nature*. Routledge, Abingdon, Oxon, UK and New York, NY, USA, 207 pp.

Pfliegner, K., J. Schuberth, D. Nissler, and G. Gumb, 2012: *Climate and Energy Policy in Germany: Mechanisms to Encourage Private Sector Investment/Participation in Low-Carbon Development. A Case-Study of Germany's Building Sector*. Prepared by the German Federal Environment Agency and KfW, OECD Publishing, Paris, France, 23 pp.

Posey, J., 2009: The determinants of vulnerability and adaptive capacity at the municipal level: evidence from floodplain management programs in the United States. *Global Environmental Change*, **19(4)**, 482-493.

Pramova, E., B. Locatelli, H. Djoudi, and O.A. Somorin, 2012: Forests and trees for social adaptation to climate variability and change. *Wiley Interdisciplinary Reviews: Climate Change*, **3(6)**, 581-596.

Praskievicz, S. and H. Chang, 2009: A review of hydrological modelling of basin-scale climate change and urban development impacts. *Progress in Physical Geography*, **33(5)**, 650-671.

Preston, B.L., E.J. Yuen, and R.M. Westaway, 2011: Putting vulnerability to climate change on the map: a review of approaches, benefits, and risks. *Sustainability Science*, **6(2)**, 177-202.

Prowse, T.D., C. Furgal, R. Chouinard, H. Melling, D. Milburn, and S.L. Smith, 2009: Implications of climate change for economic development in northern Canada: energy, resource, and transportation sectors. *AMBIO: A Journal of the Human Environment*, **38(5)**, 272-281.

Pryer, J.A., 2003: *Poverty and Vulnerability in Dhaka Slums: the Urban Livelihoods Study.* Ashgate Publishing, Aldershot, UK, 203 pp.

Przyluski, V. and S. Hallegatte (eds.), 2012: *Gestion des Risques Naturels – Leçons de la Tempête Xynthia.* Quae Editions, Versailles, France, 264 pp.

Puppim de Oliveira, J.A., 2009: The implementation of climate change related policies at the subnational level: an analysis of three countries. *Habitat International*, **33(3)**, 253-259.

Quah, A.K. and M. Roth, 2012: Diurnal and weekly variation of anthropogenic heat emissions in a tropical city, Singapore. *Atmospheric Environment*, **46**, 92-103.

Radhi, H., 2009: Evaluating the potential impact of global warming on the UAE residential buildings – a contribution to reduce the CO_2 emissions. *Building and Environment*, **44(12)**, 2451-2462.

Rahman, M.M., G. Haughton, and A.E.G. Jonas, 2010: The challenges of local environmental problems facing the urban poor in Chittagong, Bangladesh: a scale-sensitive analysis. *Environment and Urbanization*, **22(2)**, 561-578.

Ramachandraiah, C., 2011: Coping with urban flooding: a study of the 2009 Kurnool floods, India. *Environment and Urbanization*, **23(2)**, 431-446.

Ramin, B. and T. Svoboda, 2009: Health of the homeless and climate change. *Journal of Urban Health*, **86(4)**, 654-664.

Ranger, N., R. Muir-Wood, and S. and Priya, 2009: *Assessing Extreme Climate Hazards and Options for Risk Mitigation and Adaptation in the Developing World.* World Development Report 2010 Background Note, World Bank, Washington, DC, USA, 27 pp.

Ranger, N., S. Hallegatte, S. Bhattacharya, M. Bachu, S. Priya, K. Dhore, F. Rafique, P. Mathur, N. Naville, and F. Henriet, 2011: An assessment of the potential impact of climate change on flood risk in Mumbai. *Climatic Change*, **104(1)**, 139-167.

Redclift, M.R., D.M. Navarrete, and M. Pelling, 2011: *Climate Change and Human Security: The Challenge to Local Governance under Rapid Coastal Urbanization.* Edward Elgar, Cheltenham, UK, 176 pp.

Reed, S.O., R. Friend, V.C. Toan, P. Thinphanga, R. Sutarto, and D. Singh, 2013: "Shared learning" for building urban climate resilience – experiences from Asian cities. *Environment and Urbanization*, **25(2)**, 393-412.

Rees, W.E., 1992: Ecological footprints and appropriated carrying capacity: what urban economics leaves out. *Environment and Urbanization*, **4(2)**, 121-130.

Regmi, M.B. and S. Hanaoka, 2011: A survey on impacts of climate change on road transport infrastructure and adaptation strategies in Asia. *Environmental Economics and Policy Studies*, **13(1)**, 21-41.

Reid, C.E., M.S. O'Neill, C.J. Gronlund, S.J. Brines, D.G. Brown, A.V. Diez-Roux, and J. Schwartz, 2009: Mapping community determinants of heat vulnerability. *Environmental Health Perspectives*, **117(11)**, 1730-1736.

Ren, G., Z. Chu, Z. Chen, and Y. Ren, 2007: Implications of temporal change in urban heat island intensity observed at Beijing and Wuhan stations. *Geophysical Research Letters*, **34(5)**, L05711, doi:10.1029/2006GL027927.

Renn, O., 2008: *Risk Governance: Coping with Uncertainty in a Complex World.* Earthscan Risk in Society Series, Earthscan, London, UK and Sterling, VA, USA, 368 pp.

Repetto, R., 2011a: *Economic and Environmental Impacts of Climate Change in Nevada*. Dēmos, New York, NY, USA, 5 pp.

Repetto, R., 2011b: *Economic and Environmental Impacts of Climate Change in Arizona*. Dēmos, New York, NY, USA, 7 pp.

Repetto, R., 2012a: *Economic and Environmental Impacts of Climate Change in Virginia*. Dēmos, New York, NY, USA, 10 pp.

Repetto, R., 2012b: *Economic and Environmental Impacts of Climate Change in Florida*. Dēmos, New York, NY, USA, 9 pp.

Repetto, R., 2012c: *The Rising Risks of Climate Change in Massachusetts*. Energy Future Coalition, Washington DC, USA, 25 pp.

Repetto, R., 2012d: *New Mexico's Rising Climate Risks.* UN Foundation, New York, NY, USA, 11 pp.

Reuveny, R., 2007: Climate change induced migration and violent conflict. *Political Geography*, **26(6)**, 656-673.

Revi, A., 2005: Lessons from the deluge: priorities for multi-hazard risk mitigation. *Economic and Political Weekly*, 3911-3916.

Revi, A., 2008: Climate change risk: an adaptation and mitigation agenda for Indian cities. *Environment and Urbanization*, **20(1)**, 207-229.

Rim, C., 2009: The effects of urbanization, geographical and topographical conditions on reference evapotranspiration. *Climatic Change*, **97(3)**, 483-514.

Ring, I., 2008: Integrating local ecological services into intergovernmental fiscal transfers: the case of the ecological ICMS in Brazil. *Land Use Policy*, **25(4)**, 485-497.

Roaf, S., D. Crichton, and F. Nicol, 2009: *Adapting Buildings and Cities for Climate Change: A 21st Century Survival Guide.* 2nd edn., Elsevier, Oxford, UK, 385 pp.

Roberts, D., 2008: Thinking globally, acting locally – institutionalizing climate change at the local government level in Durban, South Africa. *Environment and Urbanization*, **20(2)**, 521-537.

Roberts, D., 2010: Prioritizing climate change adaptation and local level resilience in Durban, South Africa. *Environment and Urbanization*, **22(2)**, 397-413.

Roberts, D. and S. O'Donoghue, 2013: Urban environmental challenges and climate change action in Durban, South Africa. *Environment and Urbanization*, **25(2)**, 299-319.

Roberts, D., R. Boon, N. Diederichs, E. Douwes, N. Govender, A. Mcinnes, C. Mclean, S. O'Donoghue, and M. Spires, 2012: Exploring ecosystem-based adaptation in Durban, South Africa: "learning-by-doing" at the local government coal face. *Environment and Urbanization*, **24(1)**, 167-195.

Roberts, S., 2008a: Altering existing buildings in the UK. *Energy Policy*, **36(12)**, 4482-4486.

Roberts, S., 2008b: Effects of climate change on the built environment. *Energy Policy*, **36(12)**, 4552-4557.

Rockström, J., W. Steffen, K. Noone, Å. Persson, F.S. Chapin III, E. Lambin, T.M. Lenton, M. Scheffer, C. Folke, and H.J. Schellnhuber, 2009: Planetary boundaries: exploring the safe operating space for humanity. *Ecology and Society*, **14(2)**, 32, www.ecologyandsociety.org/vol14/iss2/art32/.

Romeo, C. and M. Zinzi, 2011: Impact of a cool roof application on the energy and comfort performance in an existing non-residential building. A Sicilian case study. *Energy and Buildings*, **67**, 647-657.

Romero-Lankao, P., 2007: How do local governments in Mexico City manage global warming? *Local Environment*, **12(5)**, 519-535.

Romero-Lankao, P., 2010: Water in Mexico City: what will climate change bring to its history of water-related hazards and vulnerabilities? *Environment and Urbanization*, **22(1)**, 157-178.

Romero-Lankao, P. and D. Dodman, 2011: Cities in transition: transforming urban centers from hotbeds of GHG emissions and vulnerability to seedbeds of sustainability and resilience: introduction and editorial overview. *Current Opinion in Environmental Sustainability*, **3(3)**, 113-120.

Romero-Lankao, P. and H. Qin, 2011: Conceptualizing urban vulnerability to global climate and environmental change. *Current Opinion in Environmental Sustainability*, **3(3)**, 142-149.

Rosenberg, E.A., P.W. Keys, D.B. Booth, D. Hartley, J. Burkey, A.C. Steinemann, and D.P. Lettenmaier, 2010: Precipitation extremes and the impacts of climate change on stormwater infrastructure in Washington State. *Climatic Change*, **102(1)**, 319-349.

Rosenzweig, C. and W. Solecki eds., 2010: Climate Change Adaptation in New York City: Building a Risk Management Response: New York City Panel on Climate Change 2010 Report. *Annals of the New York Academy of Sciences*, **1196**, 1-354.

Rosenzweig, C., W. Solecki, S.A. Hammer, and S. Mehrotra, 2010: Cities lead the way in climate-change action. *Nature*, **467(7318)**, 909-911.

Rosenzweig, C., W.D. Solecki, S.A. Hammer, and S. Mehrotra (eds.), 2011: *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network*. Cambridge University Press, Cambridge, UK, 286 pp.

Rosenzweig, C., W.D. Solecki, L. Parshall, B. Lynn, J. Cox, R. Goldberg, S. Hodge, S. Gaffin, R.B. Slosberg, and P. Savio, 2009: Mitigating New York City's heat island: integrating stakeholder perspectives and scientific evaluation. *Bulletin of the American Meteorological Society*, **90(9)**, 1297-1312.

Rotterdam Climate Initiative, 2010: *Rotterdam Climate Proof: Adaptation Programme 2010*. City of Rotterdam, Rotterdam, Netherlands, 30 pp.

Roy, M., D. Hulme, and F. Jahan, 2013: Contrasting adaptation responses by squatters and low-income tenants in Khulna, Bangladesh. *Environment and Urbanization*, **25(1)**, 157-176.

Roy, S.B., L. Chen, E.H. Girvetz, E.P. Maurer, W.B. Mills, and T.M. Grieb, 2012: Projecting water withdrawal and supply for future decades in the U.S. under climate change scenarios. *Environmental Science & Technology*, **46(5)**, 2545-2556.

Ruth, M., 2010: Economic and social benefits of climate information: assessing the cost of inaction. *Procedia Environmental Sciences*, **1**, 387-394.

Sabates-Wheeler, R., T. Mitchell, and F. Ellis, 2008: Avoiding repetition: time for CBA to engage with the livelihoods literature? *IDS Bulletin*, **39(4)**, 53-59.

Saber, H.H., M.C. Swinton, P. Kalinger, and R.M. Paroli, 2012: Long-term hygrothermal performance of white and black roofs in North American climates. *Building and Environment*, **50(0)**, 141-154.

Sajjad, S., B. Hussain, M. Ahmed Khan, A. Raza, B. Zaman, and I. Ahmed, 2009: On rising temperature trends of Karachi in Pakistan. *Climatic Change*, **96(4)**, 539-547.

Sakka, A., M. Santamouris, I. Livada, F. Nicol, and M. Wilson, 2012: On the thermal performance of low income housing during heat waves. *Energy and Buildings*, **49**, 69-77.

Sanchez, A.B. and P. Poschen, 2009: *The Social and Decent Work Dimensions of a New Agreement on Climate Change: A Technical Brief*. International Labour Office (ILO), Policy Integration Department, Geneva, Switzerland, 39 pp.

Sánchez-Rodríguez, R., 2009: Learning to adapt to climate change in urban areas. A review of recent contributions. *Current Opinion in Environmental Sustainability*, **1(2)**, 201-206.

Sánchez-Rodríguez, R., 2011: Urban and social vulnerability to climate variability in Tijuana, Mexico. In: *Integrating Science and Policy Vulnerability and Resilience in Global Environmental Change* [Kasperson, R. and M. Berberian (eds.)]. Earthscan, Abingdon, Oxon, UK and New York, NY, USA, pp. 187-214.

Santos, J. and S. Leite, 2009: Long-term variability of the temperature time series recorded in Lisbon. *Journal of Applied Statistics*, **36(3)**, 323-337.

Saroch, E., M. Palaniappan, D. Singh, and L. Seraydarian, 2011: *Climate Change and Urbanisation: Building Resilience in the Urban Water Sector – A Case Study of Indore, India*. Insititution for Social and Environmental Transition (ISET) and the Pacific Institute in collaboration with Taru Leading Edge, ISET, Boulder, CO, USA and Pacific Institute, Oakland, CA, USA, 92 pp.

Sassen, S., 2012: *Cities in a World Economy*. 4th edn., Pine Forge Press (Imprint of Sage Publications, Inc.), Thousand Oaks, CA, USA, 398 pp.

Satterthwaite, D., 2007: *The Transition to a Predominantly Urban World and its Underpinnings*. Human Settlements Discussion Paper Series, Theme: Urban Change No. 4, International Insitute for Environment and Development (IIED), London, UK, 91 pp.

Satterthwaite, D., 2011: How urban societies can adapt to resource shortage and climate change. *Philosophical Transactions of the Royal Society A*, **369(1942)**, 1762-1783.

Satterthwaite, D., 2013: The political underpinnings of cities' accumulated resilience to climate change. *Environment and Urbanization*, **25(2)**, 381-391.

Satterthwaite, D. and D. Mitlin, 2014: *Reducing Urban Poverty in the Global South*. Routledge, Abingdon, Oxon, UK and New York, NY, USA, 306 pp.

Satterthwaite, D. and A. Sverdlik, 2012: Energy access and housing for low-income groups in urban areas. In: *Energizing Sustainable Cities: Assessing Urban Energy* [Grubler, A. and D. Fisk (eds.)]. Earthscan, Abingdon, Oxon, UK and New York, NY, USA, pp. 73-94.

Satterthwaite, D., G. McGranahan, and C. Tacoli, 2010: Urbanization and its implications for food and farming. *Philosophical Transactions of the Royal Society B*, **365(1554)**, 2809-2820.

Savonis, M.J., V.R. Burkett, and J.R. Potter, 2008: *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I*. Synthesis and Assessment Product 4.7, U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC, USA, 439 pp.

Schaeffer, R., A.S. Szklo, A.F. Pereira de Lucena, B.S. Moreira Cesar Borba, L.P. Pupo Nogueira, F.P. Fleming, A. Troccoli, M. Harrison, and M.S. Boulahya, 2011: Energy sector vulnerability to climate change: a review. *Energy*, **38(1)**, 1-12.

Scheinberg, A., S. Spies, M.H. Simpson, and A.P.J. Mol, 2011: Assessing urban recycling in low- and middle-income countries: building on modernised mixtures. *Habitat International*, **35(2)**, 188-198.

Scherba, A., D.J. Sailor, T.N. Rosenstiel, and C.C. Wamser, 2011: Modeling impacts of roof reflectivity, integrated photovoltaic panels and green roof systems on sensible heat flux into the urban environment. *Building and Environment*, **46(12)**, 2542-2551.

Schipper, L. and M. Pelling, 2006: Disaster risk, climate change and international development: scope for, and challenges to, integration. *Disasters*, **30(1)**, 19-38.

Schmidhuber, J. and F.N. Tubiello, 2007: Global food security under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **104(50)**, 19703-19708.

Schneider, A., M. Friedl, and D. Potere, 2009: A new map of global urban extent from MODIS satellite data. *Environmental Research Letters*, **4(4)**, 044003, doi:10.1088/1748-9326/4/4/044003.

Schroeder, H. and H. Bulkeley, 2009: *Governing Climate Change Post-2012: The Role of Global Cities. Case Study: Los Angeles.* Working Paper 138, Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, UK, 44 pp.

Schroll, E., J. Lambrinos, T. Righetti, and D. Sandrock, 2011: The role of vegetation in regulating stormwater runoff from green roofs in a winter rainfall climate. *Ecological Engineering*, **37(4)**, 595-600.

Schwarz, N., A. Bauer, and D. Haase, 2011: Assessing climate impacts of planning policies – an estimation for the urban region of Leipzig (Germany). *Environmental Impact Assessment Review*, **31(2)**, 97-111.

Sen, Z., 2009: Precipitation downscaling in climate modelling using a spatial dependence function. *International Journal of Global Warming*, **1(1)**, 29-42.

Seto, K.C., B. Güneralp, and L. and Hutyra, 2012: Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences of the United States of America*, **109(40)**, 16083-16088.

Shaban, A. and R. Sharma, 2007: Water consumption patterns in domestic households in major cities. *Economic and Political Weekly*, 2190-2197.

Sharma, D. and S. Tomar, 2010: Mainstreaming climate change adaptation in Indian cities. *Environment and Urbanization*, **22(2)**, 451-465.

Shaw, A., S. Sheppard, S. Burch, D. Flanders, A. Wiek, J. Carmichael, J. Robinson, and S. Cohen, 2009: Making local futures tangible – synthesizing, downscaling, and visualizing climate change scenarios for participatory capacity building. *Global Environmental Change*, **19(4)**, 447-463.

Shaw, K. and K. Theobald, 2011: Resilient local government and climate change interventions in the UK. *Local Environment*, **16(1)**, 1-15.

Shaw, R. and IEDM Team, 2009: Climate disaster resilience: focus on coastal urban cities in Asia. *Asian Journal of Environment and Disaster Management*, **1**, 101-116.

Shaw, R. and T. Izumi, 2011: Roles of civil society in climate and disaster resilience of cities and local governments. In: *Climate and Disaster Resilience in Cities* [Shaw, R. and A. Sharma (eds.)]. Emerald Books, Bingley, UK, pp. 260-280.

Shaw, R. and A. Sharma, 2011: *Climate and Disaster Resilience in Cities.* Emerald Group Publishing, Bingley, UK, 287 pp.

Sheffield, P.E. and P.J. Landrigan, 2011: Global climate change and children's health: threats and strategies for prevention. *Environmental Health Perspectives*, **119(3)**, 291-298.

Shepherd, J.M., H. Pierce, and A.J. Negri, 2002: Rainfall modification by major urban areas: observations from spaceborne rain radar on the TRMM satellite. *Journal of Applied Meteorology*, **41(7)**, 689-701.

Shepherd, M., T. Mote, J. Dowd, M. Roden, P. Knox, S.C. McCutcheon, and S.E. Nelson, 2011: An overview of synoptic and mesoscale factors contributing to the disastrous Atlanta flood of 2009. *Bulletin of the American Meteorological Society*, **92(7)**, 861-870.

Siddiqi, A., 2011: Supporting the working but vulnerable: linkages between social protection and climate change. *Climate and Development*, **3(3)**, 209-227.

Silver, J., C. McEwan, L. Petrella, and H. and Baguian, 2013: Climate change, urban vulnerability and development in Saint-Louis and Bobo-Dioulasso: learning from across two West African cities. *Local Environment*, **18(6)**, 663-677.

Simmons, M.T., B. Gardiner, S. Windhager, and J. Tinsley, 2008: Green roofs are not created equal: the hydrologic and thermal performance of six different extensive green roofs and reflective and non-reflective roofs in a sub-tropical climate. *Urban Ecosystems*, **11(4)**, 339-348.

Simon, D., 2010: The challenges of global environmental change for urban Africa. *Urban Forum*, **21(3)**, 235-248.

Simon, D. and H. Leck, 2010: Urbanizing the global environmental change and human security agendas. *Climate and Development*, **2(3)**, 263-275.

Skaggs, R., T.C. Janetos, K.A. Hibbard, and J.S. and Rice, 2012: *Climate and Energy-Water-Land System Interactions.* Technical Report to the U.S. Department of Energy in Support of the National Climate Assessment, Report PNNL-21185, Pacific Northwest National Laboratory, Richland, WA, USA, 147 pp.

Smith, B.J., M. Gomez-Heras, and S. McCabe, 2008: Understanding the decay of stone-built cultural heritage. *Progress in Physical Geography*, **32(4)**, 439-461.

Smith, J.B., K.M. Strzepek, J. Cardini, M. Castaneda, J. Holland, C. Quiroz, T.M. Wigley, J. Herrero, P. Hearne, and J. Furlow, 2011: Coping with climate variability and climate change in La Ceiba, Honduras. *Climatic Change*, **108(3)**, 457-470.

Soares, H.M.D.C., 2009: Mudanças climáticas e cidades: contribuições para uma agenda de pesquisa a partir da periferia In: *População e Mudança Climática: Dimensões Humanas das Mudanças Ambientais Globais* [Hogan, D. and E. and Marandola (eds.)]. Uma publicação do Núcleo de Estudos de População (NEPO) e do Fundo de População das Nações Unidas (UNFPA), Núcleo de Estudos da População Universidade Estadual de Campinas (UNICAMP), Cidade Universitária Zeferino Vaz, Campinas, Brazil, pp. 279-283.

Soares, S., R.P. Ribas, and F.V. Soares, 2010: *Targeting and Coverage of the Bolsa Família Programme: Why Knowing What You Measure is Important in Choosing the Numbers*. UNDP IPC-IG Working Paper No. 71, United Nations Development Programme, International Policy Centre for Inclusive Growth (UNDP IPC-IG) and the Institute for Applied Economic Research (IPEA), Brasília, Brazil, 22 pp.

Solecki, W., 2012: Urban environmental challenges and climate change action in New York City. *Environment and Urbanization*, **24(2)**, 557-573.

Solecki, W.D. and R.M. Leichenko, 2006: Urbanization and the metropolitan environment: lessons from New York and Shanghai. *Environment: Science and Policy for Sustainable Development*, **48(4)**, 8-23.

Solecki, W., R. Leichenko, and K. O'Brien, 2011: Climate change adaptation strategies and disaster risk reduction in cities: connections, contentions, and synergies. *Current Opinion in Environmental Sustainability*, **3(3)**, 135-141.

Solnit, R., 2009: *A Paradise Built in Hell: The Extraordinary Communities that arise in Disaster*. Viking Penguin (Penguin Group, USA), New York, NY, USA, 353 pp.

Sonover, A.K., L. Whitely Binder, J. Lopez, E. Willmott, J. Kay, D. Howell, and J. Simmonds, 2007: *Preparing for Climate Change: A Guidebook for Local, Regional and State Governments.* In association with and published by ICLEI – Local Governments for Sustainability, ICLEI, Oakland, CA, USA, 172 pp.

Spearman, M. and H. McGray, 2012: *Making Adaptation Count: Concepts and Options for Monitoring and Evaluation of Climate Change Adaptation*. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Eschborn, Germany, 95 pp.

Spennemann, D.H.R. and D.W. Look (eds.), 1998: *Disaster Management Programs for Historic Sites*. Proceedings of a symposium organized by the U.S. National Park Service, Western Regional Office, San Francisco, CA in collaboration with the Western Chapter of the Association for Preservation Technology held June 27 – 29, 1997 in San Francisco, CA, Western Chapter of the Association for Preservation Technology, San Francisco, CA, USA, U.S. National Park Service, and The Johnstone Centre of Parks, Recreation, and Heritage at Charles Sturt University, Albury, Australia, U.S. Government Printing Office, Washington, DC, USA, 195 pp.

Stenek, V., J. Amado, R. Connell, O. Palin, S. Wright, B. Pope, J. Hunter, J. McGregor, W. Morgan, B. Stanley, R. Washington, D. Liverman, H. Sherwin, P. Kapelus, C. Andrade, and J.D. Pabón, 2011: *Climate Risk and Business Ports, Terminal Marítimo Muelles el Bosque*, *Cartagena*, *Colombia*, *Executive Summary*. International Finance Corporation, Washington, DC, USA, 24 pp.

Stewart, M.G., X. Wang, and M.N. Nguyen, 2011: Climate change impact and risks of concrete infrastructure deterioration. *Engineering Structures*, **33(4)**, 1326-1337.

Stone, B., 2007: Urban and rural temperature trends in proximity to large US cities: 1951-2000. *International Journal of Climatology*, **27(13)**, 1801-1807.

Susca, T., S. Gaffin, and G. Dell'Osso, 2011: Positive effects of vegetation: urban heat island and green roofs. *Environmental Pollution*, **159(8)**, 2119-2126.

Susskind, L., 2010: Policy & practice: responding to the risks posed by climate change: cities have no choice but to adapt. *Town Planning Review*, **81(3)**, 217-235.

Sussman, E., DC Major, R. Deming, P.R. Esterman, A. Fadil, E. Fisher, A. Fred Fucci, R. Gordon, C. Harris, and J.K. Healy, 2010: Law and regulation. *Annals of the New York Academy of Sciences*, **1196(1)**, 87-112.

Swart, R. and F. Raes, 2007: Making integration of adaptation and mitigation work: mainstreaming into sustainable development policies? *Climate Policy*, **7(4)**, 288-303.

Tacoli, C., 2003: The links between urban and rural development. *Environment and Urbanization*, **15(1)**, 3-12.

Tacoli, C., 2009: Crisis or adaptation? Migration and climate change in a context of high mobility. *Environment and Urbanization*, **21(2)**, 513-525.

Tait, S.J., R.M. Ashley, A. Cashman, J. Blanksby, and A.J. Saul, 2008: Sewer system operation into the 21st century, study of selected responses from a UK perspective. *Urban Water Journal*, **5(1)**, 79-88.

Tallis, M., G. Taylor, D. Sinnett, and P. Freer-Smith, 2011: Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments. *Landscape and Urban Planning*, **103(2)**, 129-138.

Tanner, T., T. Mitchell, E. Polack, and B. Guenther, 2009: *Urban Governance for Adaptation: Assessing Climate Change Resilience in Ten Asian Cities.* IDS Working Paper 315, Institute of Development Studies (IDS), Brighton, UK, 47 pp.

Tavares, A.O. and P. Santos, 2013: Re-scaling risk governance using local appraisal and community involvement *Journal of Risk Research*, doi:10.1080/13669877.2013.822915.

Tayanç, M., U. İm, M. Doğruel, and M. Karaca, 2009: Climate change in Turkey for the last half century. *Climatic Change*, **94(3)**, 483-502.

Taylor, C.A. and H.G. Stefan, 2009: Shallow groundwater temperature response to climate change and urbanization. *Journal of Hydrology*, **375(3)**, 601-612.

TEEB, 2010: *The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature: A Synthesis of the Approach*, *Conclusions and Recommendations of TEEB*. The Economics of Ecosystems and Biodiversity (TEEB), United Nations Environment Programme (UNEP), Geneva, Switzerland, 36 pp.

Teng, F. and A. Gu, 2007: *Climate Change: National and Local Policy Opportunities in China*. Foundazione Eni Enrico Mattei Note di Lavoro, Milan, Italy, 18 pp.

Thompson, W.T., T. Holt, and J. Pullen, 2007: Investigation of a sea breeze front in an urban environment. *Quarterly Journal of the Royal Meteorological Society*, **133(624)**, 579-594.

Thornbush, M. and H. Viles, 2007: Simulation of the dissolution of weathered versus unweathered limestone in carbonic acid solutions of varying strength. *Earth Surface Processes and Landforms*, **32(6)**, 841-852.

Thorsson, S., F. Lindberg, J. Björklund, B. Holmer, and D. Rayner, 2011: Potential changes in outdoor thermal comfort conditions in Gothenburg, Sweden due to climate change: the influence of urban geometry. *International Journal of Climatology*, **31(2)**, 324-335.

Tidwell, V.C., P.H. Kobos, L.A. Malczynski, G. Klise, and C.R. Castillo, 2012: Exploring the water-thermoelectric power nexus. *Journal of Water Resources Planning and Management*, **138(5)**, 491-501.

Tirpak, D., A. Ronquillo-Ballesteros, K. Stasio, and H. McGray, 2010: *Guidelines for Reporting Information on Climate Finance*. WRI Working Paper, World Resources Institute, Washington, DC, USA, 32 pp.

Tomlinson, C.J., L. Chapman, J.E. Thornes, and C.J. Baker, 2011: Including the urban heat island in spatial heat health risk assessment strategies: a case study for Birmingham, UK. *International Journal of Health Geographics*, **10(42)**, 1-14.

Tompkins, E.L., M.C. Lemos, and E. Boyd, 2008: A less disastrous disaster: managing response to climate-driven hazards in the Cayman Islands and NE Brazil. *Global Environmental Change*, **18(4)**, 736-745.

Tompkins, E.L., W.N. Adger, E. Boyd, S. Nicholson-Cole, K. Weatherhead, and N. Arnell, 2010: Observed adaptation to climate change: UK evidence of transition to a well-adapting society. *Global Environmental Change*, **20(4)**, 627-635.

Trusilova, K., M. Jung, G. Churkina, U. Karstens, M. Heimann, and M. Claussen, 2008: Urbanization impacts on the climate in Europe: numerical experiments by the PSU-NCAR Mesoscale Model (MM5). *Journal of Applied Meteorology and Climatology*, **47(5)**, 1442-1455.

Tubby, K. and J. Webber, 2010: Pests and diseases threatening urban trees under a changing climate. *Forestry*, **83(4)**, 451-459.

Tyler, S., S.O. Reed, K. Macclune, and S. Chopde, 2010: *Planning for Urban Climate Resilience: Framework and Examples from the Asian Cities Climate Change Resilience Network (ACCCRN).* Climate Resilience in Concept and Practice: ISET Working Paper 3, Institute for Social and Environmental Transition (ISET), Boulder, CO, USA, 58 pp.

UCLG, 2010: *Local Governments in the World: Basic Facts on 96 Selected Countries*. United Cities and Local Governments (UCLG), Barcelona, Spain, 100 pp.

UCLG, 2011: *Local Government Finance: The Challenges of the 21st Century.* Gold II, 2010: Second Global Report on Decentralization and Local Democracy of United Cities and Local Governments (UCLG), Barcelona, Spain, 371 pp.

UN Millennium Project, 2005: *A Home in the City: The Report of the Millennium Project Taskforce on Improving the Lives of Slum Dwellers.* United Nations Millennium Project, commissioned by the UN Secretary-General, and sponsored by UNEP on behalf of the UN Development Group, Earthscan, London, UK and Sterling, VA, USA, 158 pp.

UN DESA Population Division, 2012: *World Urbanization Prospects: The 2011 Revision.* United Nations Department of Economic and Social Affairs (UN DESA) Population Division, New York, NY, USA, esa.un.org/unpd/wup/index.htm.

UN ECLAC, 1991: *Sustainable Development: Changing Production Patterns, Social Equity, and the Environment*. United Nations Economic Commission for Latin America and the Caribbean (UN ECLAC), Mexico, DF, Mexico, 146 pp.

UNEP, 2011: *Bilateral Finance Institutions & Climate Change: A Mapping of Public Financial Flows for Mitigation and Adaptation to Developing Countries in 2010*. United Nations Environment Programme Bilateral Finance Institutions Climate Change Working Group (UNEP BFI CCWG) comprised of Agence Française de Développement (AFD), European Investment Bank (EIB), Japan International Cooperation Agency (JICA), KfW Entwicklungsbank (Germany's Development Bank), Nordic Environment Finance Corporation (NEFCO), and UNEP in collaboration with the Stockholm Environment Institute (SEI), UNEP Energy Branch, Division of Technology, Industry and Economics, Paris, France, 21 pp.

UNEP, 2012: *UN-Water Status Report on the Application of Integrated Approaches to Water Resources Management*. United Nations Environment Programme (UNEP), Nairobi, Kenya, 106 pp.

UNFCCC, 2007: *Investment and Financial Flows to Address Climate Change.* United Nations Framework Convention on Climate Change (UNFCCC), Secretariat of the UNFCCC, Bonn, Gemany, 272 pp.

UN-HABITAT, 2003a: *The Challenge of Slums: Global Report on Human Settlements 2003*. United Nations Human Settlements Programme (UN-HABITAT), Earthscan Publications Ltd, London, UK and Sterling, VA, USA, 310 pp.

UN-HABITAT, 2003b: *Water and Sanitation in the World's Cities: Local Action for Global Goals*. Earthscan Publications Ltd, London, UK and Sterling, VA, USA, 274 pp.

UN-HABITAT, 2007: *Enhancing Urban Safety and Security: Global Report on Human Settlements 2007.* Earthscan Publications Ltd, London, UK and Sterling, VA, USA, 448 pp.

UN-HABITAT, 2011a: *Cities and Climate Change: Global Report on Human Settlements 2011*. Earthscan Publications Ltd, London, UK and Washington, DC, USA, 279 pp.

UN-HABITAT, 2011b: *Colored Water: Assessment of Climate Change Vulnerability in Kelurahan Pabean Pekalongan, Central Java.* UN-HABITAT, Jakarta, Indonesia, 34 pp.

UN-HABITAT, 2011c: *Adaptation Finance: Are Cities in Developing Countries Slipping Through the Cracks?* Cities and Climate Change Initiative Policy Note 1, UN-HABITAT, Nairobi, Kenya, 4 pp.

UN-HABITAT, 2012a: *Urban Patterns for a Green Economy: Leveraging Density.* UN-HABITAT, Nairobi, Kenya, 96 pp.

UN-HABITAT, 2012b: *Urban Patterns for a Green Economy: Clustering for Competitiveness.* UN-HABITAT, Nairobi, Kenya, 78 pp.

UN-HABITAT, 2012c: *Urban Patterns for a Green Economy: Optimizing Infrastructure.* UN-Habitat, Nairobi, Kenya, 79 pp.

UN-HABITAT, 2012d: *Urban Patterns for a Green Economy: Working with Nature.* UN-HABITAT, Nairobi, Kenya, 74 pp.

UNISDR, 2008: *Links between Disaster Risk Reduction, Development, and Climate Change.* Report Prepared by United Nations International Strategy for Disaster Reduction (UNISDR) for Sweden's Commission on Climate Change and Development, UNISDR Secretariat, Geneva, Switzerland, 5 pp.

UNISDR, 2009: *Global Assessment Report on Disaster Risk Reduction 2009 – Risk and Poverty in a Changing Climate: Invest Today for a Safer Tomorrow.* United Nations International Strategy for Disaster Reduction (UNISDR), UNISDR Secretariat, Geneva, Switzerland, 207 pp.

UNISDR, 2011: *Global Assessment Report on Disaster Risk Reduction 2011 – Revealing Risk, Redefining Development.* United Nations International Strategy for Disaster Reduction (UNISDR), UNISDR Secretariat, Geneva, Switzerland, 178 pp.

UNISDR, 2013: *Global Assessment Report on Disaster Risk Reduction 2013 – From Shared Risk to Shared Value: The Business Case for Disaster Risk Reduction.* United Nations International Strategy for Disaster Reduction (UNISDR), UNISDR Secretariat, Geneva, Switzerland, 246 pp.

Urwin, K. and A. Jordan, 2008: Does public policy support or undermine climate change adaptation? Exploring policy interplay across different scales of governance. *Global Environmental Change*, **18(1)**, 180-191.

Vairavamoorthy, K., S.D. Gorantiwar, and A. Pathirana, 2008: Managing urban water supplies in developing countries – climate change and water scarcity scenarios. *Physics and Chemistry of the Earth, Parts A/B/C*, **33(5)**, 330-339.

Vale, L.J. and T.J. Campanella, 2005: *The Resilient City: How Modern Cities Recover From Disaster.* Oxford University Press, New York, NY, USA, 376 pp.

van Aalst, M.K., T. Cannon, and I. Burton, 2008: Community level adaptation to climate change: The potential role of participatory community risk assessment. *Global Environmental Change*, **18(1)**, 165-179.

Van der Brugge, R. and R. De Graaf, 2010: Linking water policy innovation and urban renewal: the case of Rotterdam, The Netherlands. *Water Policy*, **12(3)**, 381-400.

van Vuuren, D.P., P.L. Lucas, and H. Hilderink, 2007: Downscaling drivers of global environmental change: enabling use of global SRES scenarios at the national and grid levels. *Global Environmental Change*, **17(1)**, 114-130.

Vano, J.A., N. Voisin, L. Cuo, A.F. Hamlet, M.M. Elsner, R.N. Palmer, A. Polebitski, and D.P. Lettenmaier, 2010: Climate change impacts on water management in the Puget Sound region, Washington State, USA. *Climatic Change*, **102(1)**, 261-286.

Vellinga, T. and M. De Jong, 2012: Approach to climate change adaptation in the port of Rotterdam. In: *Maritime Transport and the Climate Change Challenge* [Asariotis, R. and H. Benamara (eds.)]. Earthscan, Abingdon, Oxon, UK and New York, NY, USA, pp. 305-319.

Vescovi, L., A. Bourque, G. Simonet, and A. Musy, 2007: Climate change science knowledge transfer in support of vulnerability, impacts and adaptation activities on a North American regional scale: Ouranos as a case study. In: *IPCC TGICA Regional Expert Meeting: Integrating Analysis of Regional Climate Change and Response Options, Meeting Report: Participants Papers.* The Intergovernmental Panel on Climate Change (IPCC) Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA), IPCC Secretariat, Geneva Switzerland, pp. 241-245.

Viguié, V. and S. Hallegatte, 2012: Trade-offs and synergies in urban climate policies. *Nature Climate Change*, **2(5)**, 334-337.

Vojinovic, Z. and J. Van Teeffelen, 2007: An integrated stormwater management approach for small islands in tropical climates. *Urban Water Journal*, **4(3)**, 211-231.

von Hesse, M., J. Kamiche, and C. de la Torre, 2008: *Contribucion Tematica de America Latina al Informe Bienal de Evaluacion Mundial Sobre la Reduccion de Riesgo 2009*. Contribution to the GTZ-UNDP Background paper prepared for the 2009 Global Assessment Report on Disaster Risk Reduction, United Nations Secretariat, United Nations Office for Disaster Risk Reduction (UNISDR), Geneva, Switzerland, 131 pp.

Von Ritter, K. and D. Black-Layne, 2013: *Crowdfunding for Climate Change: A New Source of Finance for Climate Action at the Local Level?* ECBI Policy Brief, European Capacity Building Initiative (ECBI), Oxford, UK, 15 pp.

Voyde, E., E. Fassman, and R. Simcock, 2010: Hydrology of an extensive living roof under sub-tropical climate conditions in Auckland, New Zealand. *Journal of Hydrology*, **394(3)**, 384-395.

Vugrin, E.D. and M. Turnquist, 2012: *Design for Resilience in Infrastructure Distribution Networks*. SANDIA REPORT: SAND2012-6050, Sandia National Laboratories, Albuquerque, NM, USA, 39 pp.

Wackernagel, M., J. Kitzes, D. Moran, S. Goldfinger, and M. Thomas, 2006: The ecological footprint of cities and regions: comparing resource availability with resource demand. *Environment and Urbanization*, **18(1)**, 103-112.

Walsh, C.L., R.J. Dawson, J.W. Hall, S.L. Barr, M. Batty, A.L. Bristow, S. Carney, A.S. Dagoumas, A.C. Ford, and C. Harpham, 2011: Assessment of climate change mitigation and adaptation in cities. *Proceedings of the ICE – Urban Design and Planning*, **164(2)**, 75-84.

Walsh, C.L., D. Roberts, R.J. Dawson, J.W. Hall, A. Nickson, and R. and Hounsome, 2013: Experiences of integrated assessment of climate impacts, adaptation and mitigation modelling in London and Durban. *Environment and Urbanization*, **25(2)**, 361-380.

Wamsler, C., 2007: Bridging the gaps: stakeholder-based strategies for risk reduction and financing for the urban poor. *Environment and Urbanization*, **19(1)**, 115-142.

Wang, H.G., M. Montoliu-Munoz, and N.F.D. and Gueye, 2009: *Preparing to Manage Natural Hazards and Climate Change Risks in Dakar, Senegal: A Spatial and Institutional Approach*. Pilot Study Report, World Bank, Washington, DC, USA, 91 pp.

Warner, R., 2009: Secular regime shifts, global warming and Sydney's water supply. *Geographical Research*, **47(3)**, 227-241.

Watt, S. and J. Chamberlain, 2011: Water, climate change, and maternal and newborn health. *Current Opinion in Environmental Sustainability*, **3(6)**, 491-496.

Weaver, C., X. Liang, J. Zhu, P. Adams, P. Amar, J. Avise, M. Caughey, J. Chen, R. Cohen, and E. Cooter, 2009: A preliminary synthesis of modeled climate change impacts on U.S. regional ozone concentrations. *Bulletin of the American Meteorological Society*, **90(12)**, 1843-1863.

White-Newsome, J.L., B.N. Sánchez, E.A. Parker, J.T. Dvonch, Z. Zhang, and M.S. O'Neill, 2011: Assessing heat-adaptive behaviors among older, urban-dwelling adults. *Maturitas*, **70(1)**, 85-91.

WHO, 2011: *Air Quality and Health*. Fact Sheet No. 313, World Health Organization (WHO), Geneva, Switzerland, www.who.int/mediacentre/factsheets/fs313/en/.

WHO and WMO, 2012: *Atlas of Health and Climate*. WMO No. 1098, World Health Organization (WHO) and World Meteorological Organization (WMO), WHO Press, Geneva, Switzerland, 64 pp.

Wilbanks, T.J. and R.W. Kates, 2010: Beyond adapting to climate change: embedding adaptation in responses to multiple threats and stresses. *Annals of the Association of American Geographers*, **100(4)**, 719-728.

Wilbanks, T., P. Romero-Lankao, M. Bao, F. Berkhout, S. Cairncross, J. Ceron, M. Kapshe, R. Muir-Wood, and R. Zapata-Marti, 2007: Chapter 7: Industry, settlement and society. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 357-390.

Wilbanks, T., S. Fernandez, G. Backus, P. Garcia, K. Jonietz, P. Kirshen, M. Savonis, W. Solecki, and L. Toole, 2012: *Climate Change and Infrastructure, Urban Systems, and Vulnerabilities.* Technical Report for the U.S. Department of Energy in support of the National Climate Assessment, Oak Ridge National Laboratory, Oak Ridge, TN, USA, 87 pp.

Wilby, R., 2007: A review of climate change impacts on the built environment. *Built Environment*, **33(1)**, 31-45.

Wilby, R.L. and R. Keenan, 2012: Adapting to flood risk under climate change. *Progress in Physical Geography*, **36(3)**, 348-378.

Wilkinson, S.J. and R. Reed, 2009: Green roof retrofit potential in the central business district. *Property Management*, **27(5)**, 284-301.

Willems, P., 2013: Revision of urban drainage design rules after assessment of climate change impacts on precipitation extremes at Uccle, Belgium. *Journal of Hydrology*, **496**, 166-177.

Willems, P. and K. Arnbjerg-Nielsen, 2013: Climate change as a driver for urban drainage paradigm change. *Water21*, **15(1)**, 23-24.

Willems, P. and M. Vrac, 2011: Statistical precipitation downscaling for small-scale hydrological impact investigations of climate change. *Journal of Hydrology*, **402(3)**, 193-205.

Willems, P., J. Olsson, K. Arnbjerg-Nielsen, S. Beecham, A. Pathirana, I.B. Gregersen, H. Madsen, and V.T.V. Nguyen, 2012: *Impacts of Climate Change on Rainfall Extremes and Urban Drainage Systems.* International Water Association (IWA) Publishing, London, UK, 226 pp.

Wilson, E., 2006: Adapting to climate change at the local level: the spatial planning response. *Local Environment*, **11(6)**, 609-625.

Wilson, E. and J. Piper, 2008: Spatial planning for biodiversity in Europe's changing climate. *European Environment*, **18(3)**, 135-151.

Wilson, E., C. Termeer, H.P. Mees, and P.P.J. and Driessen, 2011: Adaptation to climate change in urban areas: climate-greening London, Rotterdam, and Toronto. *Climate Law*, **2(2)**, 251-280.

Wilson, G., 2012: *Community Resilience and Environmental Transitions.* Routledge, Abingdon, Oxon, UK and New York, NY, USA, 251 pp.

WMO, 2008: *Future Climate Change Research and Observations: GCOS, WCRP and IGBP Learning from the IPCC Fourth Assessment Report*. Workshop and Survey Report, IGBP Report No. 58 (WMO/TD No. 1418), Global Climate Observing System (GCOS) Secretariat, World Climate Research Programme (WCRP) Joint Planning Staff – World Meteorological Organization (WMO), and the International Geosphere-Biosphere Progamme (IGBP) Secretariat, WMO, Geneva, Switzerland, 57 pp.

Wong, T. and R. Brown, 2009: The water sensitive city: principles for practice. *Water Science and Technology*, **60(3)**, 673-682.

World Bank, 2008: *World Development Report 2009: Reshaping Economic Geography*. The International Bank for Reconstruction and Development / The World Bank, Washington DC, USA, 383 pp.

World Bank, 2010a: *World Development Report 2010: Development and Climate Change*. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 417 pp.

World Bank, 2010b: *Climate Risks and Adaptation in Asian Coastal Megacities: A Synthesis Report*. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 97 pp.

World Bank, 2010c: *Mainstreaming Gender in Road Transport: Operational Guidance for World Bank Staff*. Transport Papers TP-28, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 43 pp.

World Bank, 2010d: *Economics of Adaptation to Climate Change: Synthesis Report.* The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 101 pp.

World Bank, 2010e: *Natural Hazards, UnNatural Disasters: The Economics of Effective Prevention.* The United Nations International Strategy for Disaster Reduction (UNISDR) and Global Facility for Disaster Reduction and Recovery (GFDRR), the World Bank, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 254 pp.

World Bank, 2011: *North African Coastal Cities: Climate Change Adaptation and Natural Disaster Preparedness in the Coastal Cities of North Africa – Summary of Regional Study.* Marseille Center for Mediterranean Integration (CMI) and the World Bank, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 23 pp.

World Bank, 2012: *Inclusive Green Growth: The Pathway to Sustainable Development*. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 171 pp.

World Bank, 2013: *Urban Resilience and World Bank Investments: Disaster Risk Management and Climate Change Adaptation in Urban Areas – First Phase Report.* Urbanization and Resilience Management Unit (UDRUR) and the Global Facility for Disaster Reduction and Recovery (GFDRR) of the Urban and Disaster Risk Management Department (UDR), World Bank, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 60 pp.

World Economic Forum, 2013: *Global Risks 2013*. 8th edn., An Initiative of the Risk Response Network, World Economic Forum, Geneva, Switzerland, 78 pp.

Xu, T., J. Sathaye, H. Akbari, V. Garg, and S. Tetali, 2012: Quantifying the direct benefits of cool roofs in an urban setting: reduced cooling energy use and lowered greenhouse gas emissions. *Building and Environment*, **48(0)**, 1-6.

Young, O.R., 2002: *The Institutional Dimensions of Environmental Change: Fit, Interplay, and Scale.* MIT Press, Cambridge, MA, USA, 221 pp.

Zanchettin, D., P. Traverso, and M. Tomasino, 2007: Observations on future sea level changes in the Venice lagoon. *Lagoons and Coastal Wetlands in the Global Change Context: Impacts and Management Issues*, **192**, 41-53.

Zetter, R. and G. Deikun, 2010: Meeting humanitarian challenges in urban areas. *Forced Migration Review*, **34**, 5-7.

Zhang, J., Y.H. Sui, and X.B. Geng, 2011: Landscape design of urban green space adaptive to global climate change: a review. *Advanced Materials Research*, **243**, 6842-6845.

Ziervogel, G., P. Johnston, M. Matthew, and P. Mukheibir, 2010: Using climate information for supporting climate change adaptation in water resource management in South Africa. *Climatic Change*, **103(3)**, 537-554.

Zimmerman, R. and C. Faris, 2010: Chapter 4: Infrastructure impacts and adaptation challenges. *Annals of the New York Academy of Sciences*, **1196(1)**, 63-86.

Zimmerman, R. and C. Faris, 2011: Climate change mitigation and adaptation in North American cities. *Current Opinion in Environmental Sustainability*, **3(3)**, 181-187.

Zinzi, M. and S. Agnoli, 2012: Cool and green roofs. An energy and comfort comparison between passive cooling and mitigation urban heat island techniques for residential buildings in the Mediterranean region. *Energy and Buildings*, **55(0)**, 66-76.

9 Rural Areas

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This chapter should be cited as:
Dasgupta, P., J.F. Morton, D. Dodman, B. Karapinar, F. Meza, M.G. Rivera-Ferre, A. Toure Sarr, and K.E. Vincent, 2014: Rural areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 613-657.

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Executive Summary

Rural areas still account for almost half the world's population, and about 70% of the developing world's poor people. {9.1.1} There is a lack of clear definition of what constitutes rural areas, and definitions that do exist depend on definitions of the urban. {9.1.2} Across the world, the importance of peri-urban areas and new forms of rural-urban interactions are increasing (*limited evidence*, *high agreement*). {9.1.3} Rural areas, viewed as a dynamic, spatial category, remain important for assessing the impacts of climate change and the prospects for adaptation. {9.1.1}

Climate change in rural areas will take place in the context of many important economic, social, and land-use trends (*very high confidence*). In different regions, absolute rural populations have peaked or will peak in the next few decades. {9.3.1} The proportion of the rural population depending on agriculture is extremely varied across regions, but declining everywhere. Poverty rates in rural areas are higher than overall poverty rates, but also falling more sharply, and the proportions of population in extreme poverty accounted for by rural people are also falling: in both cases with the exception of sub-Saharan Africa, where these rates are rising. {Figure 9-2} Accelerating globalization, through migration, labor linkages, regional and international trade, and new information and communication technologies, is bringing about economic transformation in rural areas of both developing and developed countries. {9.3.1}

Rural people in developing countries are subject to multiple non-climate stressors, including under-investment in agriculture (though there are signs this is improving), problems with land and natural resource policy, and processes of environmental degradation (*very high confidence*). In developing countries, the levels and distribution of rural poverty are affected in complex and interacting ways by processes of commercialization and diversification, food policies, and policies on land tenure. In developed countries, there are important shifts toward multiple uses of rural areas, especially leisure uses, and new rural policies based on the collaboration of multiple stakeholders, the targeting of multiple sectors, and a change from subsidy-based to investment-based policy. {9.3.1, Table 9-3}

Impacts of climate change on the rural economic base and livelihoods, land use, and regional interconnections are at the latter stages of complex causal chains (*high confidence*). These flow through changing patterns of extreme events and/or effects of climate change on biophysical processes in agriculture and less-managed ecosystems. {9.3.3} This increases both the uncertainty associated with detection and attribution of current impacts {9.3.2}, and with projections of specific future impacts. {9.3.3}

Structural features of farm households and communities affect their vulnerability to climate change in complex ways (*high confidence*). There is *low agreement* on some of the key factors associated with vulnerability or resilience in rural areas {9.3.5.1}, including rainfed as opposed to irrigated agriculture {9.3.5.1.1}, small-scale and family-managed farms, and integration into world markets. {9.3.5.1.2} There is *high agreement* on the importance for resilience of access to land and natural resources, flexible local institutions {9.3.5.1.3}, and knowledge and information {9.3.5.1.6}, and on the association of gender inequalities with vulnerability. {9.3.5.1.5} Specific livelihood niches such as pastoralism, mountain farming systems, and artisanal fisheries are vulnerable and at high risk of adverse impacts (*high confidence*), partly owing to neglect, misunderstanding, or inappropriate policy toward them on the part of governments. {9.3.5.2}

Cases in the literature of observed impacts on rural areas often suffer from methodological problems of attribution, but evidence for observed impacts, both of extreme events and other categories, is increasing (*medium confidence*). Impacts attributable to climate change include some direct impacts of droughts, storms, and other extreme events on infrastructure and health (*low confidence* globally, but *medium confidence* in certain regions), as well as longer-term declining yields of major crops, from which impacts on income and livelihoods can be inferred with *low confidence*. There is *high confidence* in geographically specific impacts, such as glacier melt in the Andes. {9.3.2}

Major impacts of climate change in rural areas will be felt through impacts on water supply, food security {9.3.3.1}, and agricultural incomes {9.3.4.1} (*high confidence*). Shifts in agricultural production, of food and non-food crops, are projected for many areas of the world (*high confidence*). {9.3.3.1} Price rises, which may be induced by climate shocks as well as other factors {9.3.3.3.2}, have a disproportionate impact on the welfare of the poor in rural areas, such as female headed households and those with limited access to modern agricultural inputs, infrastructure, and education. {9.3.3.1} The time scale for impacts varies across regions and sectors, and by the nature of the specific climatic impact.

Climate change will impact international trade volumes in both physical and value terms (*limited evidence*, *medium agreement*). Importing food can help countries adjust to climate change-induced domestic productivity shocks while short-term food deficits in low-income countries may have to be met through food aid. Options exist for adaptations within international agricultural trade (*medium confidence*). Deepening agricultural markets and improving the predictability and the reliability of the world trading system through trade reform, as well as investing in additional supply capacity of small-scale farms in developing countries, could result in reduced market volatility and manage food supply shortages caused by climate change. {9.3.3.3.2}

Migration patterns will be driven by multiple factors of which climate change is only one (*high confidence*). {9.3.3.3.1} Given these multiple drivers of migration (economic, social, political, demographic, and environmental) and the complex interactions that mediate migratory decision making by individuals or households, establishment of a relation between climate change and intra-rural and rural-to-urban migration, observed or projected, remains a major challenge.

Climate policies, such as increasing energy supply from renewable resources, encouraging cultivation of biofuels, or payments under Reducing Emissions from Deforestation and Forest Degradation (REDD), will have significant secondary impacts, both positive (increasing employment opportunities) and negative (landscape changes, increasing conflicts for scarce resources), in some rural areas (*medium confidence*). {9.3.3.4} There is a need to understand how implementation of these policies will impact on rural livelihoods. These secondary impacts, and trade-offs between mitigation and adaptation in rural areas, have implications for governance, including the need to promote participation of rural stakeholders.

Most studies using valuation methodologies conclude that climate change impacts will be substantial, especially for developing countries, owing to their economic dependence on agriculture and natural resources, low adaptive capacities, and geographical locations (*very high confidence*). {9.3.4} Valuation of climate impacts needs to draw on both monetary and non-monetary indicators. The valuation of non-marketed ecosystem services {9.3.4.5} and the limitations of economic valuation models that aggregate across multiple contexts {9.3.4} pose challenges for valuing impacts in rural areas (*high confidence*).

There is a growing body of literature on adaptation practices in both developed and developing country rural areas {9.4.1}, including documentation of practical experience in agriculture, water, forestry and biodiversity, and, to a lesser extent, fisheries {9.4.3} (*very high confidence*). Public policies supporting decision making for adaptation exist in developed and, increasingly, in developing countries, and there are also examples of private adaptations led by individuals, companies, and non-governmental organizations (*high confidence*). {9.4.2} Constraints on adaptation come from lack of access to credit, land, water, technology, markets, knowledge and information, and perceptions of the need to change; and are particularly pronounced in developing countries (*high confidence*). {9.4.4} Gender and institutions affect access to adaptation options and the presence of barriers to adaptation (*very high confidence*). {9.4.4}

9.1. Introduction

9.1.1. Rationale for the Chapter

This chapter assesses the impacts of climate change on, and the prospects for adaptation in, rural areas. Rural areas include diverse patterns of settlement, infrastructure, and livelihoods, and relate in complex ways with urban areas. The chapter shows that rural areas experience specific vulnerabilities to climate change, both through their dependence on natural resources and weather-dependent activities and their relative lack of access to information, decision making, investment, and services. Adaptation strategies will need to address these vulnerabilities. Some of the key starting points, which affect the scope and coverage of literature assessed in this chapter, are as follows:

- Rural areas, even after significant demographic shifts, still account for 3.3 billion people, or almost half (47.9%) of the world's total population (UN DESA Population Division, 2013).
- The overwhelming majority of the world's rural population (3.1 billion people, or 91.7% of the world's rural population, or 44.0% of the world's total population) live in less developed or least developed countries (UN DESA Population Division, 2013).
- Rural dwellers also account for about 70% of the developing world's poor people. IFAD (2010) states that around 70% of the extreme poor in developing countries lived in rural areas in 2005. Ravallion et al. (2007), using 2002 data and poverty lines of US$1.08 or US$2.15, in each case with urban poverty lines adjusted upward to recognize additional non-food spending, give a figure of around 75% of people, under either poverty line, being rural.
- Rural areas are a spatial category, associated with certain patterns of human activity, but with those associations being subject to continuous change.
- Rural areas are largely defined in contradistinction to urban areas, but that distinction is increasingly seen as problematic.
- Rural populations have, and will have, a variety of income sources and occupations, within which agriculture and the exploitation of natural resources have privileged, but not necessarily predominant, positions.

The chapter will complement the treatment of issues also dealt with in Chapters 4 and 7, but will primarily look at how biophysical impacts of climate change on agriculture and on less-managed ecosystems translate into impacts on human systems, and in this regard will complement sections of Chapters 12 and 13 and other sectoral and regional chapters. The important impacts of climate change on human health are covered in Chapter 11. In accordance with the proportion of the rural population found in developing countries, literature on these countries is given prominence, but issues of impact, vulnerability, and adaptation in developed countries are also assessed.

9.1.2. Definitions of the Rural

"Rural" refers generally to areas of open country and small settlements, but the definition of "rural areas" in both policy-oriented and scholarly literature are terms often taken for granted or left undefined, in a process of definition that is often fraught with difficulties (IFAD, 2010).

Frequently Asked Questions

FAQ 9.1 | What is distinctive about rural areas in the context of climate change impacts, vulnerability, and adaptation?

Nearly half of the world's population, approximately 3.3 billion people, lives in rural areas, and 90% of those people live in developing countries. Rural areas in developing countries are characterized by a dependence on agriculture and natural resources; high prevalence of poverty, isolation, and marginality; neglect by policymakers; and lower human development. These features are also present to a lesser degree in rural areas of developed countries, where there are also closer interdependencies between rural and urban areas (such as commuting), and where there are also newer forms of land use such as tourism and recreational activities (although these also generally depend on natural resources).

The distinctive characteristics of rural areas make them uniquely vulnerable to the impacts of climate change because:

- Greater dependence on agriculture and natural resources makes them highly sensitive to climate variability, extreme climate events, and climate change.
- Existing vulnerabilities caused by poverty, lower levels of education, isolation, and neglect by policymakers can all aggravate climate change impacts in many ways.

Conversely, rural people in many parts of the world have, over long time scales, adapted to climate variability, or at least learned to cope with it. They have done so through farming practices and use of wild natural resources (often referred to as indigenous knowledge or by similar terms), as well as through diversification of livelihoods and through informal institutions for risk-sharing and risk management. Similar adaptations and coping strategies can, given supportive policies and institutions, form the basis for adaptation to climate change, although the effectiveness of such approaches will depend on the severity and speed of climate change impacts.

Table 9-1 | Indicative examples of definitions of the "rural" and the "urban" in selected countries.

Country	Term	Definition	Reference
Australia	Major urban area	Population of more than 100,000	Australian Bureau of Statistics (2013)
	Other urban area	Population of 1000–99,999	
	Rural area	Includes small towns with a population of 200–999	
China	Major urban area	Population of more than 10,000	Ministry of Construction (1993)
	Medium urban area	Population of 3000–9999	
	Small urban area	Population of fewer than 3000	
	Major village	Population of 1000–3000	
	Medium village	Population of 300–1000	
	Small village	Population of fewer than 300	
India	Urban area	Population of 5000 or more; **or** where at least 75% of the male working population is non-agricultural; **or** having a density of population of at least 400 people km^{-2}. It is implied that all non-urban areas are rural.	Government of India (2012)
Jamaica	Urban place	Population of more than 2000 people; and provision of a certain set of amenities and facilities that are deemed to indicate "modern living". It is implied that all non-urban areas are rural.	Statistical Institute of Jamaica (2012:iv)
United States of America	Rural area	All territory outside of defined urbanized areas and urban clusters, that is, open country and settlements with fewer than 2500 residents; with population densities as high as 386 people km^{-2}.	Womach (2005)

Ultimately, in developing countries as well as developed countries, the rural is defined as the inverse or the residual of the urban (Lerner and Eakin, 2010). Human settlements in fact exist along a continuum from "rural" to "urban," with "large villages," "small towns," and "small urban centers" not clearly fitting into one or the other. The variations in definitions from country to country can best be described through several examples (from both developed and developing countries of different sizes) shown in Table 9-1.

Researchers have increasingly recognized that the simple dichotomy between "rural" and "urban" is extremely problematic (Simon et al., 2006, p. 4). Additional categories such as "peri-urban areas" (Webster 2002; Bowyer-Bower, 2006; Simon et al., 2006; Simon, 2008; Lerner and Eakin, 2010) and "desakota" (McGee, 1991; Desakota Study Team, 2008; Moench and Gyawali, 2008) allow more nuanced analysis of the permeable boundaries of rural and urban areas and the diversified economic systems that exist across the urban-rural spectrum; see Box CC-UR.

While remaining aware of issues of definition, this chapter in general assesses the literature on rural areas using whatever definitions of the rural are used in that literature. Global statistics collated by international organizations and cited here are generally aggregations of national statistics compiled under each national definition.

9.2. Findings of Recent Assessments

The Fourth Assessment Report (AR4) of the IPCC contains no specific chapter on "rural areas." Material on rural areas and rural people is found throughout the AR4, but rural areas are approached from specific viewpoints and through specific disciplines. Table 9-2 summarizes key findings on rural areas from AR4 (particularly Easterling et al. (2007) on agriculture; Wilbanks et al. (2007) on industry, settlement, and society; and Klein et al. (2007) on links between adaptation and mitigation), and relevant findings from the International Assessment of Agricultural Knowledge, Science and Technology for Development (McIntyre et al., 2009). All of these sources stress uncertainty, the importance of non-climate trends, complexity, and context-specificity in any findings on rural areas and climate change.

9.3. Assessing Impacts, Vulnerabilities, and Risks

9.3.1. Current and Future Economic, Social, and Land Use Trends in Rural Areas

Climate change in rural areas will take place against the background of the trends in demography, economics, and governance that are shaping those areas. While there are major points of contact between the important trends in developing and developed countries, and the analytical approaches used to discuss them, it is easier to discuss trends separately for the two groups of countries. In particular there is a close association in developing countries between rural areas and poverty. Table 9-3 summarizes and compares the most important trends across the two groups of countries. Figures 9-1 and 9-2 and Table 9-4 focus on two specific trends in developing countries: demographic trends and trends in poverty indicators.

9.3.2. Observed Impacts

Documentation of observed impacts of climate change on rural areas involves major questions of detection and attribution (see Chapter 18). Whilst having potential, there are complications with using traditional knowledge and farmer perceptions to detect climate trends (Rao et al., 2011; see also Box 18-4). Implied equivalence between local perceptions of climate change, local decadal trends, extreme events, and global change is common, and often used without systematic discussion of the challenges (Paavola, 2008; Ensor and Berger, 2009; Castro et al., 2012). This is not a problem in the context of detailed social-scientific analysis of vulnerability, adaptive capacity, and their determinants, but becomes more problematic to use as evidence for observed impact. Detection and attribution of extreme events to climate change is no

less challenging (Seneviratne et al., 2012). Exposure to non-climate trends and shocks further complicates the issue (Nielsen and Reenberg, 2010; see also Section 3.2.7).

The impacts of climate change on patterns of settlement, livelihoods, and incomes in rural areas will be the result of multi-step causal chains of impact. Typically, those chains will be of two sorts. One sort will involve extreme events, such as floods and storms, as they impact on rural infrastructure and cause direct loss of life. The other sort will involve impacts on agriculture or on ecosystems on which rural people depend. These impacts may themselves stem from extreme events, from changing patterns of extremes due to climate change, or from changes in mean conditions. The detection and attribution of extreme events is discussed by the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (Seneviratne et al., 2012). The detection and attribution of impacts on ecosystems and on agriculture are dealt with in Chapters 4 and 7 of this report. Both exercises are complex.

Seneviratne et al. (2012) give a detailed and critical assessment of the detection and attribution of observed patterns of extreme events, which shows greatly varying levels of confidence in the attribution to climate change of global and regional trends, and that "attribution of single extreme events to anthropogenic climate change is challenging" (p. 112). They state that it is *likely* there has been a worldwide increase in extreme high-water events during the late 20th century, with a *likely* anthropogenic influence on it. They have *medium confidence* in detecting trends toward more intense and frequent droughts in some parts of the world (southern Europe and West Africa) since 1950. They note that opposite trends exist elsewhere, and that there is *low confidence* in any trend in drought in, for example, East Africa. WG I AR5 Chapter 2 similarly ascribes *low confidence* in a global observed trend in drought in the later 20th century, with a *likely* increase in frequency and intensity of drought in the Mediterranean and West Africa and a *likely* decrease in central North America. Lyon and DeWitt (2012) see a "recent and abrupt decline in the East African long rains" since 1999. Seneviratne et al. (2012) assign *low confidence* to any observed long-term increases in

Table 9-2 | Relevant findings on rural areas from the IPCC Fourth Assessment Report and the International Assessment of Agricultural Science and Technology for Development.

	Finding	Source
Importance of non-climate trends	The significance of climate change needs to be considered in the multi-causal context of its interactions with other non-climate sources of change and stress (e.g., water scarcity, governance structures, institutional and jurisdictional fragmentation, limited revenue streams for public sector roles, resource constraints, or inflexible land use patterns).	W 7.4.2 I 6.7.5
	Different development paths may increase or decrease vulnerabilities to climate-change impacts.	W 7.7
	Neglect by policymakers and underinvestment in infrastructure and services has negatively affected rural areas.	I 1.3.4
	Policy neglect specifically disfavors rural women.	I 1.3.4
	Assessment of climate change impacts on agriculture has to be undertaken against a background of demographic and economic trends in rural areas.	E 5.3.2
	Global numbers of people at risk from hunger will be affected by climate change, but more by socioeconomic trends as captured in the difference between the SRES scenarios.	E 5.6.5
Specific characteristics of smallholder agriculture	Subsistence and smallholder livelihood systems suffer from a number of non-climate stressors, but are also characterized by having certain resilience factors (efficiencies associated with the use of family labor, livelihood diversity to spread risks).	E 5.3.2
	Traditional knowledge of agriculture and natural resources is an important resilience factor.	I 2.1.2, 3.2.2, 3.2.3 E 5.3.2 CC4
	The combination of stressors and resilience factors gives rise to complex and locally specific impacts, resistant to modeling.	E 5.4.7 W 7.2, 7.4, 7.5
Impacts on agriculture and agricultural trade	In low-latitude regions, temperature increases of 1–2°C are likely to have negative impacts on yields of major cereals. Further warming has increasingly negative impacts in all regions.	E 5.4.2
	Increases in global mean temperatures (GMTs) of 2–3°C might lead to a small rise or decline (10–15%) in food (cereals) prices, while GMT increases in the range of 5.5°C or more might result in an increase in food prices of, on average, 30%.	E 5.6.1
Forestry	Loss of forest resources through climate change may affect 1.2 billion poor and forest-dependent people, including through impacts on non-timber forest products.	E 5.4.5
Valuation	Robust valuation of climate change impact on human settlements is difficult, and social and environmental costs are poorly captured by monetary metrics: non-monetary valuation methods should be explored.	W 7.4.3, 7.5 I 8.2.5
Adaptation	The need and the capacity to adapt vary considerably from region to region, and from farmer to farmer.	I 1.3.3
	Adaptation actions can be effective in achieving their specific goals, but they may have other (positive or negative) effects, including resource competition.	I 6.7.5
	Diversification of agricultural and non-agricultural livelihood strategies is an important adaptation trend, but requires institutional support and access to resources.	E 5.5.1, 5.5.2
	The effectiveness of adaptation efforts is likely to vary significantly between and within regions, depending on geographic location, vulnerability to current climate extremes, level of economic diversification and wealth, and institutional capacity.	I 6.8
	Multi-stakeholder processes are increasingly important with respect to climate change adaptation.	I 7.5.3
Links between adaptation and mitigation	Mitigation and adaptation policies are in many cases, and certainly for agriculture, closely linked.	K 18.4.3, 18.7.1 E 5.4.1, 5.4.2, 5.6.5 W 7.1, 7.7

Sources: W = Wilbanks et al. (2007); E = Easterling et al. (2007); I = McIntyre et al. (2009); K = Klein et al. (2007); CC4 = Cross-Chapter Case Study C4 "Indigenous knowledge for adaptation to climate change" in AR4 (Parry et al., 2007).

tropical cyclone activity, as does WGI AR5 Chapter 2, and to attribution of any changes in cyclone activity to anthropogenic influence. WGI AR5 Chapter 2 states that an observed increase in the frequency and intensity of North Atlantic cyclones is *virtually certain*. It also describes varying regional trends toward heavy precipitation events, *very likely* in central North America. Section 3.2.7 ascribes *medium confidence* to observed increased likelihood of flooding at the scale of some regions.

Handmer et al. (2012) discuss both observed and projected impacts of extreme events on human systems and ecosystems, with numerous examples of diverse, widespread negative impacts (see also Chapter 18). Important categories of extreme events causing negative impacts in rural areas include tropical storms and droughts: Hurricane Stan in October 2005 affected nearly 600,000 people on the Chiapas coast as a consequence of flooding and sudden river overflows (Saldaña-Zorrilla, 2008). Droughts in rural areas produce severe economic stresses, including employment reduction and migration (Gray and Mueller, 2012). Agricultural livelihoods are affected by droughts. Ericksen et al. (2012) review a variety of livestock mortality rates for recent droughts in the Horn of Africa, ranging up to 80% of livestock in southern Kenya in 2009.

Climate change impacts on agriculture and ecosystems run through rising temperature and changes in rainfall variability and seasonality as well as through extreme events. Changes in temperature caused reduction in global yields of maize and wheat by 3.8 and 5.5% respectively from 1980 to 2008 relative to a counterfactual without climate change, which offset in some countries some of the gains from improved agricultural technology (Lobell et al., 2011; see also Section 7.2.1.1). Badjeck et al. (2010) discuss current and future impacts on fisherfolk across the world. Many local-level studies are subject to the attribution problems mentioned above, but Wellard et al. (2012) cautiously note a convergence of climate data with the perceptions of farmers and officials to the effect that over the last 30 years the rainfall in Malawi has become less predictable, that the rainy season is arriving later in the year causing delays in planting

Table 9-3 | Major demographic, poverty-related, economic, governance, and environmental trends in rural areas of developed and developing countries.

	Developed countries	Developing countries
Demographic trends	Rural population accounts for 22.3% of the total population (or about 276 million people) (UN-DESA Population Division, 2012). Rural areas account for 75% of land area in OECD countries (OECD, 2006). Rural population has peaked (absolute numbers) in Europe and North America. Rural depopulation in some places, but also counter-urbanization with people moving from urban to rural areas elsewhere.	Rural population accounts for 50.3% of the total population (or about 2.5 billion people) in less developed countries (excluding LDCs), 71.5% (or about 608 million people) in LDCs. Rural population has already peaked in Latin America and the Caribbean, East and Southeast Asia; expected to peak around 2025 in the Middle East, North Africa, South and Central Asia; around 2045 in sub-Saharan Africa.
Dependence on agriculture	Agriculture accounts for only 13% of rural employment in the EU (OECD, 2006), and less than 10% on average across developed countries; however, it has a strong indirect influence on rural economies. Increased competition as a result of economic globalization has resulted in agriculture no longer being the main pillar of the rural economy in Europe. Economic policies are primary drivers, with social re-composition and economic restructuring taking place (Marsden, 1999; Lopez-i-Gelats et al., 2009).	Proportion of rural population engaged in agriculture declining in all regions (Figure 9-2). Agriculture still provides jobs for 1.3 billion smallholders and landless workers (World Bank, 2008). Non-agricultural including labor-based and migration-based livelihoods increasingly existing alongside (and complementing) farm-based livelihoods. Agricultural initiatives and growth still important for adaptation and for smallholders in Africa and Asia (Collier et al., 2008; Osbahr et al., 2008; Kotir, 2011).
Poverty and inequality	Per capita gross domestic product (GDP) in rural areas of OECD countries is only 83% of national average (but significant variation within and between countries): driven by out-migration, aging, lower educational attainment, lower productivity of labor, low levels of public services (OECD, 2006).	Rates of poverty (percentage of population living on less than US$2 per day) and extreme poverty (percentage of population living on less than US$1.25 per day) falling in rural areas in most parts of the world; but rural poverty and rural extreme poverty rising in sub-Saharan Africa. Recent price hikes and volatility exacerbated hunger and malnutrition among rural households, many of which are net food-buyers (FAOSTATS, 2013). Hunger and malnutrition prevalent among rural children in South Asia and sub-Saharan Africa (World Bank, 2007; IFAD, 2010); see Figure 9-2 and Table 9-4.
Economic, policy, governance trends	Shift from agricultural (production) to leisure (consumption) activities; focus on broader amenity values of rural landscapes for recreation, tourism, forests, and ecosystem services (OECD, 2006; Rounsevell et al., 2006; Bunce, 2008). Agricultural subsidies under pressure from international trade negotiations and domestic budgetary constraints. As a result of recent price hikes, domestic price support has been lowered in OECD countries. New policy approach in OECD countries that focuses on investments and targets a range of rural economic sectors and environmental services.	Interconnectedness and economic openness in rural areas have encouraged shifts to commercial agriculture, livelihoods diversification and help knowledge transfers (Section 9.3.3). Interlinkages between land tenure, food security, and biofuel policies impact rural poverty (see Sections 7.1 and 7.2.2 for further details). Decentralization of governance and emergence of rural civil society. Movements toward land reform in some parts of Asia (Kumar, 2010). Emergence of economies in transition, characterized in places by coexistence of leading and lagging regions; political and democratic decentralization leading to increasing complexity of policy (World Bank, 2007).
Environmental degradation	Different socioeconomic scenarios have varying impacts on land use and agricultural biodiversity (Reidsma et al., 2006).	Resource degradation, environmentally fragile lands subject to overuse and population pressures, exacerbating social and environmental challenges. Multiple stressors increase risk, reduce resilience, and exacerbate vulnerability among rural communities from extreme events and climate change impacts (Section 13.2.6).
Rural-urban linkages and transformations	Changes in land use and land cover patterns at urban-rural fringe affected by new residential development, local government planning decisions, and environmental regulations (Brown, D.G. et al., 2008).	Stronger rural-urban linkages through migration, commuting, transfer of public and private remittances, regional and international trade, inflow of investment, and diffusion of knowledge (through new information and communication technologies) (IFAD, 2010). Continued out-migration to urban areas by the semiskilled and low-skilled, reducing the size of the rural workforce (IFAD, 2010). Trend for migration to small and medium-sized towns (Sall et al., 2010). Increased volumes of agricultural trade, growing by 5% on average (annually) between 2000 and 2008 (WTO, 2009). New initiatives of foreign direct investment (FDI) in agriculture in the form of large-scale land acquisitions in developing countries (World Bank, 2010; Anseeuw et al., 2012).

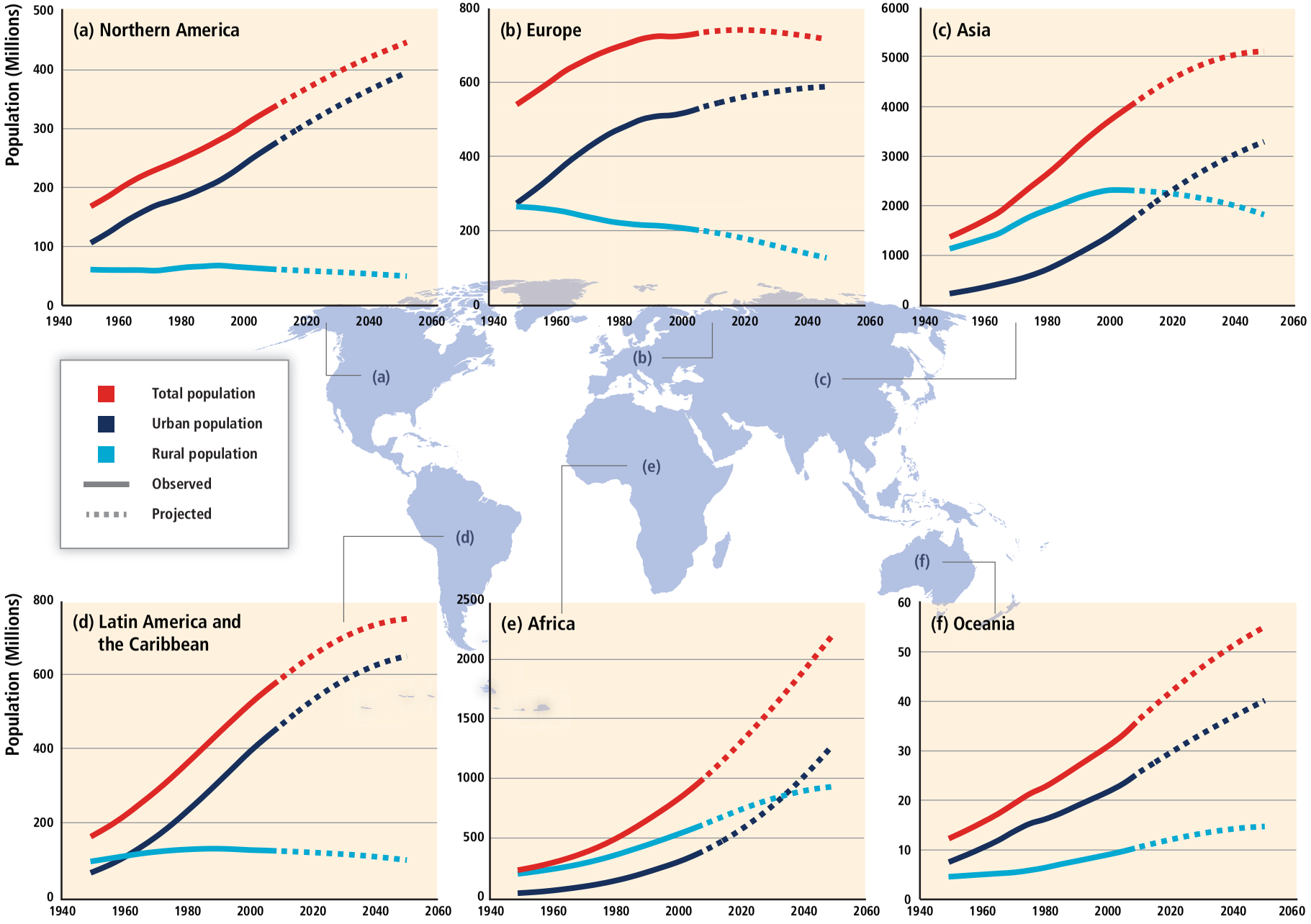

Figure 9-1 | Trends in rural, urban, and total populations by region; solid lines represent observed values and dotted lines represent projections (UN DESA Population Division, 2013). Note: Regions used in the source do not correspond with the IPCC regions covered in Chapters 22–30.

Table 9-4 | Poverty indicators for rural areas of developing countries. Source: Adapted from IFAD (2010).

	Incidence of poverty (%)		Incidence of rural poverty (%)		Incidence of extreme poverty (%)		Incidence of extreme rural poverty (%)		Rural people as % of those in extreme poverty	
	1988	2008	1988	2008	1988	2008	1988	2008	1988	2008
Developing world	69.1	51.2	83.2	60.9	45.1	27.0	54.0	34.2	80.5	71.6

Note: the incidence of extreme poverty and poverty is defined as percentage of people living on less than US$1.25 per day and less than US$2 per day, respectively.

of the main crops, and that damaging dry spells during the rainy season have become more frequent.

Glacial retreat in Latin America is one of the best evidenced current impacts on rural areas (see Section 27.3.1.1). In highland Peru there have been rapid observed declines since 1962 in glacier area and dry-season stream flow, on which local livelihoods depend, which accord well with local perceptions of changes that are necessitating adaptation (Orlove, 2009). Other studies of the area focus both on observed changes in water availability and on glacial lake outburst floods, which are attributable to climate change (Carey, 2010; Bury et al., 2011; Carey et al., 2012). There is also a rich specialized literature on the impacts of shrinking sea ice and changing seasonal patterns of ice formation and melt on indigenous peoples in the Arctic (Ford, 2009; Beaumier and Ford, 2010; see also Section 28.2.5.1.7).

Migration associated with weather-related extremes or longer-term climate trends is discussed in Table 12-3, with empirical examples of migrations linked to droughts, coastal storms, floods, and sea level rise. The Asian Development Bank (ADB, 2012) gives a figure of 42 million people displaced by extreme weather events in Asia and the Pacific over 2010–2011. Attribution of migration to climate change is extremely complex, as recognized by Black et al. (2011a), because life in rural areas across the world typically involves complex patterns of rural-urban and rural-rural migration, subject to economic, political, social, and demographic drivers, patterns that are modified or exacerbated by climate events and trends rather than solely caused by them (see also Section 12.4.1).

9.3.3. Future Impacts

This section examines the major impacts of climate change identified or projected for rural areas, under the headings of economic base and livelihoods; infrastructure; spatial and regional interconnections, including migration, trade, investment, and knowledge; and second-order impacts of climate policy. Section 9.3.4 assesses the literature on impact through a different and specific lens, that of economic valuation. The biophysical impacts of climate change on food crops are dealt with primarily in Chapter 7; but also here and in Section 9.3.4 insofar as they affect rural economies. Biophysical impacts on non-food cash crops are discussed below. As with the observed impacts in Section 9.3.2, the future impacts of climate change described here, and quantified in Section 9.3.4, are at the latter stages of complex causal chains that flow through changing patterns of extreme events and/or effects of climate change on biophysical processes in agriculture and less-managed ecosystems. Lal et al. (2011) show the regional specificity of projected socioeconomic impacts across the rural USA, with different regions affected through agriculture, water stress, and energy costs. Anderson et al. (2010) discuss the complexity of projected impacts across dryland regions of developing countries. These considerations increase the uncertainty associated with any particular impact on the economic base, on land use, or on regional interconnections.

9.3.3.1. Economic Base and Livelihoods

9.3.3.1.1. General considerations

Climate change will affect rural livelihoods, or "the capabilities, assets (stores, resources, claims, and access) and activities required for a means of living" (Chambers and Conway, 1992, p. 6). Many, though by no means all, rural livelihoods are dependent on natural resources (e.g., agriculture, fishing, and forestry), and their availability will vary in a changing climate. This will have effects on human security and well-being (Kumssa and Jones, 2010; see also Chapter 12). Climate change impacts on smallholder and subsistence farmers will be compounded by environmental and physical processes affecting production at a landscape, watershed, or community level; and other impacts, including those on human health and on non-agricultural livelihoods (Morton, 2007) and also trade and food prices (Anderson et al., 2010). Despite the growing importance of non-farm livelihoods in rural areas worldwide (Ellis, 2000; Reardon et al., 2007), and households pursuing interdependent agricultural and non-agricultural livelihoods in peri-urban areas as a risk management strategy (Lerner and Eakin, 2010; Lerner et al., 2013), there is a relative scarcity of literature on the interactions of these with climate variability and climate change.

Climate variability and change interacts with, and sometimes compounds, existing livelihood pressures in rural areas, such as economic policy, globalization, environmental degradation, and HIV/AIDS, as has been shown in Tanzania (Hamisi et al., 2012), Ghana (Westerhoff and Smit, 2009), South Africa (Reid and Vogel, 2006; Ziervogel and Taylor, 2008; O'Brien et al., 2009), Malawi (Casale et al., 2010), Kenya (Oluoko-Odingoa, 2011), Senegal (Mbow et al., 2008), and India (O'Brien et al., 2004). Economic heterogeneity of farm households within communities, in terms of farm and household size, crop choices, and input use, will be important in determining impacts (Claessens et al., 2012), as will social relations within households that affect production (Morton, 2007).

Projected impacts on yields and production of food crops are assessed in Section 7.4.1 and Figure 7-7. Local warming in excess of 1°C is projected to have negative impacts in both temperate and tropical regions without adaptation (though individual locations may benefit). There is *medium confidence* in large negative impacts of local increases of 3°C to 4°C, on productivity, production, and food security, globally and particularly

in tropical countries, that go beyond adaptive capacity. The impacts of climate change on the agricultural sector in Africa, dominated by smallholder farming and very largely rainfed, are considered to be very significant to economies and livelihoods (Collier et al., 2008; Hassan, 2010; Kotir, 2011; Müller et al., 2011). These results emerge across a range of scenarios. Several other studies also map declines in net revenues from crops and the associated links with food security and poverty (Thurlow and Wobst, 2003; Reid et al., 2008; Molua, 2009; Thurlow et al., 2009).

Post-harvest aspects of agriculture—storage on-farm and commercially, handling, and transport—have been relatively neglected in discussions of climate change, but will be affected by changes in temperature, rainfall, humidity, and by extreme events. Many adaptation opportunities are

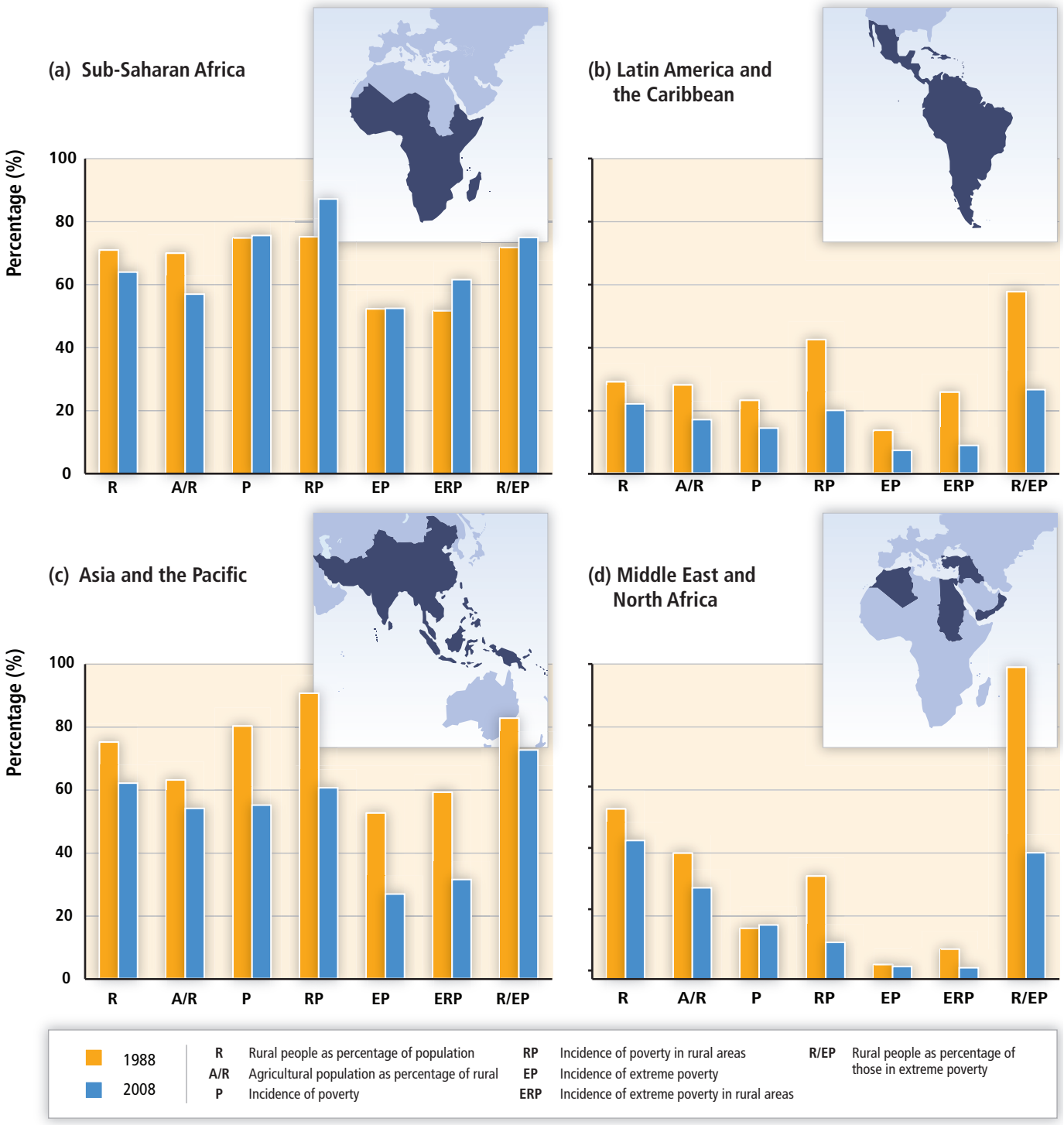

Figure 9-2 | Demographic and poverty indicators for rural areas of developing countries, by region (adapted from IFAD, 2010). Shaded countries are those for which data were available in the original source. Note: Regions used in the source do not correspond with the IPCC regions covered in Chapters 22–30.

already understood by post-harvest service providers, but getting post-harvest knowledge into use at scale is a significant challenge (Stathers et al., 2013; see also Tefera, 2012). Future impacts on production and storage will affect prices. Food crises in Africa triggered by moderate declines in agricultural production have been exacerbated by "exchange entitlement failures"—food price spikes and asset price collapses (Devereux, 2009). Rising food prices negatively affect many rural people who are net food buyers (see Table 7-1), and the poorest of the poor in rural areas—female-headed households (which tend to be poorer than male-headed households) and those who have limited access to land, modern agricultural inputs, infrastructure, and education (Ruel et al., 2010).

The remainder of this section discusses issues around climate impacts on agricultural livelihoods, other than food crop production: water as an input to agriculture, non-food crops, livestock, and fisheries.

9.3.3.1.2. Water

Water supply will be impacted through climate change (Chapter 3). In rural areas groundwater extraction and irrigation water availability is crucial for agricultural livelihoods but is typically not included in modeled projections of future crop yields, as discussed by Lobell and Field (2012). At the same time, non-climate trends including population growth and lack of adequate regulatory frameworks will greatly affect demand for water by agriculture and other competing uses, as discussed by Macdonald (2010) for the southwestern USA, by Juana et al. (2008) for South Africa, and by multiple authors for the Middle East (Iglesias et al., 2010; Chenoweth et al., 2011; Sowers et al., 2011; Hanafi et al., 2012; Rochdane et al., 2012; Verner, 2012).

At the continental level in Africa, analysis of existing rainfall and recharge studies suggests that climate change will not lead to widespread catastrophic failure of improved rural groundwater supplies, but it could affect a population of up to 90 million people, as they live in rural areas where annual rainfall is between 200 and 500 mm yr^{-1}, and where decreases in annual rainfall, changes in intensity, or seasonal variations may cause problems for groundwater supply (Macdonald et al., 2009). At higher resolution groundwater resources are threatened (e.g., in South Africa; Knüppe, 2011), and multiple water crises are expected to result from the increasing demand, further affecting people in rural areas (Nkem et al., 2011). Climate change is expected to impact water resources in the Asian region in a major way. Immerzeel et al. (2010), in a study of the Indus, Ganges, Brahmaputra, Yangtze, and Yellow River basins, conclude that different river basins would experience different impacts on water availability and food security due to climate change. They further argue that the Brahmaputra and Indus basins would be more susceptible to changes in water availability affecting the food security of 60 million people. In southern Europe, declines in rainfall and meltwater from glacial ice and snow would increase the costs of production and living (Falloon and Betts, 2010). Drought could threaten biodiversity and traditional ecosystems particularly in southern Europe, with problems exacerbated by declining water quality. Decline in economic activity may increase rural depopulation and harm the development of rural communities in southern Europe (Westhoek et al., 2006).

9.3.3.1.3. Non-food crops and high-value food crops

Non-food crops and high-value food crops, such as cotton, wine grapes, beverage crops, and other cash crops, which represent an important source of livelihood in many rural areas, have received less attention than staple food crops when assessing the impacts of climate change. Literature on biofuels such as jatropha focuses on the impacts of biofuels on climate change rather than on the effects of climate on yields and other relevant variables in these agricultural systems. Where crops have dual use as food and biofuel (e.g., oilseeds, sugarcane, sugar beet, maize, and wheat) impacts can be inferred from studies that focus on their use for food.

The findings of Easterling et al. (2007), that cotton yields would decrease as changes in temperature and precipitation overcome potential benefits of increasing carbon dioxide (CO_2), have been corroborated in other findings, such as those of Haim et al. (2008, p. 433) that cotton cultivation in Israel will decline by 52% and 38% by 2070–2100 under the SRES A2 and B2 scenarios, and that the net revenue will also decrease by 240% and 173% in both scenarios. Few systematic assessments have been done on other fiber crops such as jute, kenaf, and flax.

Climate change impacts on wine grapes have been extensively studied and documented. Climate impacts such as increasing number of hot days and decreasing frost risk may benefit some varieties. Lobell et al. (2006) assess the impacts of climate change on yields of six perennial crops in California by 2099, and report that the production of wine grapes will experience relatively small changes compared to other commodities during the concerned period. The uncertainty analysis shows the yield variations are limited within 10%, although Gatto et al. (2009) argue that the revenue of the industry in Napa, California, could decline by 2034. Jones et al. (2005) indicate that future climate change will exceed climatic thresholds affecting ripening for existing varieties grown at the margins of their climatic limits. Warmer conditions could also lead to more poleward locations becoming more conducive to grape growing and wine production.

Lobell and Field (2012) model impacts on 20 perennial crops in California under the A2 and B1 scenarios; of the four crops with the most reliable models cherry yields are projected to decline by nearly 20%, strawberries and table grapes to experience smaller declines, and almonds a slight positive trend. These projections do not incorporate adaptation options or possible decline in irrigation water supply, which would limit production. Yields of several cash crops in the Middle East such as olives, apples, and pistachios may decline if winter temperatures are too high (Verner, 2012).

The case of tropical beverage crops, in particular coffee, is discussed in Box 9-1, and projected changes in area suitable for all three tropical beverage crops are set out in Table 9-5.

9.3.3.1.4. Livestock

The impacts of climate change on livestock—which form a part of a variety of farming systems (Devendra et al., 2005)—are seen by Thornton et al. (2009) as a neglected research area complicated by other

Box 9-1 | Impacts of Climate Change on Tropical Beverage Crops

The major traded beverage crops coffee, tea, and cocoa support the livelihoods of several million small-scale producers in more than 60 countries of the tropics of Africa, Asia, and Latin America. Coffee production has long been recognized as sensitive to climate variability, with global production and prices sensitive to occasional frosts in Brazil—the world's largest producer (Varangis et al., 2003). Likewise the livelihoods of millions of small producers are dependent both on stability of production and stability in world prices. During the last crash in coffee prices from 2000–2003 poverty levels in the coffee growing regions of Nicaragua increased, while they fell in the rest of the country (World Bank, 2003); subsequently during the drought associated with El Niño in 2005 coffee productivity fell to between a third and half of normal, similarly leading to severely reduced income for small producers (Haggar, 2009).

Gay et al. (2006), analyzing the effects of recent climate change on coffee producing areas in Veracruz, Mexico, have developed econometric models of the relationship between coffee productivity and fluctuations in temperature and precipitation, which gave an R^2 of 0.69 against historical data. Extrapolating the historical tendencies in temperature and precipitation to 2020 and applying their econometric model, they predict that coffee production is *likely* to decline by 34%, and this decline in production takes producers from making net profits of on average around US$200 per acre to less than US$20 per acre. This has led to a series of studies projecting the effects of climate change on the distribution of Arabica coffee growing areas of the coming decades summarized below and in Table 9-5.

For Brazil, Assad et al. (2004) and Pinto et al. (2007) have mapped the changes in area suitable for coffee production in the four main coffee producing states. A 3°C increase in temperature and 15% increase in rainfall (taken from the general prediction of climate change for southern Brazil in the IPCC Third Assessment Report of 2001) would lead to major changes in the distribution of coffee producing zones. In the main coffee producing states of Minas Gerais and São Paulo the potential area for production would decline from 70 to 75% of the states to 20 to 25%, production in Gioas would be eliminated, but the area would be reduced only by 10% in Parana. New areas suitable for production in Santa Catarina and Rio Grande do Sul will only partially compensate the loss of area in other states (Pinto and Assad, 2008). The economic impacts of a rise in temperature of 3°C would cause a 60% decline in coffee production in the state of São Paulo equal to nearly US$300 million income (Pinto et al., 2007).

Models developed by CIAT predict the distribution of coffee under the A2A climate scenario using a statistical downscaling of the climate change data from 20 different General Circulation Models (GCMs) used in the IPCC Fourth Assessment. They use WorldClim data to characterize the current distribution of coffee using 19 climatic variables and then use the climate data downscaled to 1, 5, and 10 km resolution to map where those conditions may occur in the future (2020 or 2050). This method has been applied to coffee distribution in Kenya (CIAT, 2010), Central America, and Mexico (Laderach et al., 2010; Glenn et al., 2013); tea production in Kenya (CIAT, 2011a) and Uganda (CIAT, 2011b); and cocoa production in Ghana and Côte d'Ivoire (CIAT, 2011c; Laderach et al., 2013) (Table 9-5). The suitability for coffee crops in Costa Rica, Nicaragua, and El Salvador will be reduced by 40% (Glenn et al., 2013) while the loss of climatic niches in Colombia will force the migration of coffee crops toward higher altitudes by mid-21st century (Ramirez-Villegas et al., 2012). In the same way, increases in temperature will affect tea production, in particular at low altitudes (Wijeratne, et al., 2007). Only one similar study has been done for Robusta coffee (Simonett, 2006), in Uganda, which shows similarly drastic changes in both distribution and total area suitable for coffee production.

Effects are also expected on the incidence of pests and diseases in these crops. Increased generations under climate change for the coffee nematode have been predicted for Brazil (Ghini et al., 2008). Jaramillo et al. (2011) conclude that Coffee Berry Borer (*Hypothenemus hampei*) distribution in East Africa has expanded as a result of rising temperatures, and predicts, based on A2A and B2B scenarios of Met Office Hadley Centre climate prediction model 3 (HadCM3), that it will spread to affect the main coffee producing areas of Ethiopia, Kenya, Uganda, Rwanda, and Burundi by 2050.

Continued next page →

Box 9-1 (continued)

At a minimum climate change will cause considerable changes in the distribution of these crops, disrupting the livelihoods of millions of small-holder producers. In many cases the area suitable for production would decrease considerably with increases of temperature of only 2°C to 2.5°C. Although some local areas may experience improved conditions for coffee production, for example, high-altitude areas of Guatemala, the overall predictions are for a reduction in area suitable for coffee production by 2050 in all countries studied (Laderach et al., 2010).

drivers of change, rapid change in livestock systems, spatial heterogeneity, and social inequality between livestock keepers. They review various pathways of impact on livestock. Impacts through drought will be significant, as will heat stress, particularly of *Bos taurus* cattle. Impacts through animal health and disease will be even harder to predict than other categories of impact (Thornton et al., 2009). Franco et al. (2011) reveal significant declines in forage for ranching in California under SRES scenarios B1 and A2.

Pastoralists, who are dependent on livestock grazed in arid, semiarid, or mountainous areas, display very specific combinations of adaptive capacity, especially through mobility and vulnerability, as discussed in Section 9.3.5. Ericksen et al. (2012), with particular reference to East Africa, discuss possibilities of loss of rangeland productivity, changes in rangeland composition toward browse species, and changes in herd dynamics through more frequent droughts as possible impacts. In the Middle East, rangelands will be under substantial climate stress, which may reduce their carrying capacity, in light of the growing demand for meat products and the region's growing livestock population (Verner, 2012, p. 166). Little et al. (2001) discuss impacts of floods, directly and through disease, on pastoral herds. Similarly in the Ferlo Region in northern Senegal, modest reduction in rainfall of 15% in combination with a 20% increase in rainfall variability could have considerable effects on livestock stocking density and profits, reducing the optimal stocking density by 30%, based on six GCMs (Hein et al., 2009).

As extensive livestock production is associated with semiarid areas marginal for cropping, some authors project shifts toward livestock production under climate change. Modeled data from across Africa on the net income per unit of land from crops and different livestock species show that farmers are more likely to keep livestock, compared to crop cultivation, as temperatures increase and as precipitation decreases. Within livestock production, beef production will decline and sheep and goat production increase (Seo and Mendelsohn, 2007a). Large-scale commercial beef cattle farmers are most vulnerable to climate change, particularly because they are less likely to have diversified (Seo and Mendelsohn, 2007b). Kabubo-Mariara (2009) shows for non-pastoral areas of Kenya the nonlinear relationship of livestock production to climate change, whereby increased mean precipitation of 1% could reduce revenues from livestock by 6%. Jones and Thornton (2009) identify major transition zones across Africa where increased probability of drought up to 2050 will create conditions for shifts from cropping to livestock.

9.3.3.1.5. Fisheries

Impacts of climate change on aquatic ecosystems will have adverse consequences for the world's 36 million fisherfolk, through multiple pathways including changes in fish stock distribution and abundance, and destruction of fishing gear and infrastructure in storms and severe

Table 9-5 | Projected changes in areas suitable for production of tropical beverage crops by 2050.

Crop	Countries	Change in climate by 2050	Change in total area by 2050	Change in distribution by 2050 (in meters above sea level)
Coffee	Guatemala, Costa Rica, Nicaragua, El Salvador, Honduras, Mexico[6]	2.0–2.5°C increase in temperature 5–10% decline in total rainfall	Between 38% and 89% decline in area suitable for production	Minimum altitude suitable for production rise from 600 to 1000
	Kenya[1]	2.3°C increase in temperature Rainfall increase from 1405 mm to 1575 mm	Substantial decline in suitability of western highlands, some decline in area optimal for production in eastern highlands	Minimum altitude for production rise from 1000 to 1400
Tea	Kenya[2]	2.3°C increase in temperature Rainfall increase from 1655 mm to 1732 mm	Majority of western highlands lose suitability, while losses are compensated by gains at higher altitude in eastern highlands	Optimum altitude for production change from 1500–2100 to 2000–2300
	Uganda[3]	2.3°C increase in temperature Rainfall increase from 1334 mm to 1394 mm	Considerable reduction in suitability for production across all areas	Optimal altitude change from 1450–1650 to 1550–1650
Cocoa	Ghana, Côte d'Ivoire[4,5]	2.1°C increase in temperature No change in total rainfall	Considerable reduction in area suitable for production; almost total elimination in Ivory Coast without adaptation measures	Optimal altitude change from 100–250 to 450–500

Sources: [1]CIAT (2010); [2]CIAT (2011a); [3]CIAT (2011b); [4]CIAT (2011c); [5]Laderach et al. (2013); [6]Glenn et al. (2013). Projections use the SRES A2 scenario; the projection methodology is described in Box 9-1.

weather events (Badjeck et al., 2010; see also Sections 5.4.3.3, 6.4.1.1, 7.4.2, 30.6.2.1). An indicator approach (assessing climate change impacts together with the high share of fisheries as a source of income) showed that economies with the highest vulnerability of capture fisheries to climate change were in central and western Africa (e.g., Malawi, Guinea, Senegal, and Uganda), Peru and Colombia in northwestern South America, and four tropical Asian countries (Bangladesh, Cambodia, Pakistan, and Yemen) (Allison et al., 2009). In China, Japan, and South Korea, changes in climate and social systems could have a negative impact on fisheries, adversely affecting livelihoods and food security of the region (Kim, 2010).

9.3.3.2. Infrastructure

Assessments of the impacts of climate change on infrastructure take a general or urban perspective and do not focus on rural areas, though rural impacts can be inferred. River flooding and sea level rise will produce temporary loss of land and land activities, and damage to transportation infrastructure particularly on coastal areas (Kirshen et al., 2008), with specific evidence from North America (Hess et al., 2008). Flooding events may cause sediment transport and damage roads and bridges (Nearing et al., 2004) as well as affecting reservoir storing capacity. Importantly, in rural areas usually there are few alternatives once a road is blocked and that may increase vulnerability of rural areas when facing extreme hydroclimatological events that impact transportation infrastructure (NRC, 2008). Climate change will affect the operation of existing water infrastructures (Kundzewicz et al., 2008). Some documented impacts on dams, reservoirs, and irrigation infrastructure include reduction of sediment load due to reductions in flows (associated with lower precipitation), positively affecting infrastructure operation (Wang et al., 2007); impacts of climate variability and change on storage capacity that creates further vulnerability (Lane et al., 1999); and failures in the reliability of water allocation systems (based on water use rights) due to reductions of streamflows under future climate scenarios (Meza et al., 2012).

In Arctic Canada and Alaska, infrastructure built for very cold weather will deteriorate as the air and ground warm. Larsen et al. (2008) estimate, using the Atmosphere-Ocean General Circulation Model (AOGCM) intercomparison project and an A1B scenario, increases in public infrastructure costs of 10 to 20% through 2030 and 10% through 2080 for Alaska, amounting to several billion dollars, much of it to be spent outside of urban centers. Lemmen et al. (2008) reports that foundation fixes alone in the largely rural Northwest Territories could cost up to CAN$420 million, and that nearly all of northern Canada's extensive winter road network, which supplies rural communities and supports extractive industries which bring billions of dollars to the Canadian economy annually, is at risk (Furgal and Prowse, 2008) from a 2°C to 4°C change in ground surface temperatures, which would imply a cost of replacement with all-weather roadways of CAN$85,000 per kilometer, over several decades.

9.3.3.3. Spatial and Regional Interconnections

In both developing and developed countries, rural areas have been increasingly integrated with the rest of world. The main channels through which this rapid integration process takes place are migration (permanent and cyclical), commuting, transfer of public and private remittances, regional and international trade, inflow of investment, and diffusion of knowledge through new information and communication technologies (IFAD, 2010), as well as the spatial intermingling of rural and urban economic activities (see Box CC-UR).

9.3.3.3.1. Migration

It is difficult to establish a causal relationship between environmental degradation and migration (see Section 12.4.1). Many authors argue that migration will increase during times of environmental stress (e.g., Brown and Crawford, 2008; Afifi, 2011; Kniveton et al., 2011; Gray and Mueller, 2012), and will lead to an increase in abandonment of settlements (McLeman, 2011). Climate variability has been associated with rural-urban migration (Mertz et al., 2011; Parnell and Walawege, 2011). Another body of literature argues that migration rates are no higher under conditions of environmental or climate stress (Cohen, 2004; Brown, 2008; van der Geest and de Jeu, 2008; Tacoli, 2009; McLeman and Hunter, 2010; Black et al., 2011a,b; Foresight, 2011; Gemenne, 2011; van der Geest, 2011). For Tacoli (2009) the current alarmist predictions of massive flows of so-called "environmental refugees" or "environmental migrants" are not supported by past experiences of responses to droughts and extreme weather events, and predictions for future migration flows are tentative at best. Analogies with past migration experiences are used frequently in such studies (McLeman and Hunter, 2010). For example, in Ghana the causality of migration was established to be relatively clear in the case of sudden-onset environmental perturbations such as floods, whereas in case of slow-onset environmental deterioration, there was usually a set of overlapping causes—political and socioeconomic factors—that come into play (van der Geest, 2011). Similarly, a recent survey by Mertz et al. (2010) has argued that climate factors played a limited role in past adaptation options of Sahelian farmers. Given the multiple drivers of migration (Black et al., 2011a,b) and the complex interactions that mediate migratory decision making by individual or households (McLeman and Smit, 2006; Raleigh, 2008; Black et al., 2011a,b; Kniveton et al., 2011), the projection of the effects of climate change on intra-rural and rural-to-urban migration remains a major challenge.

9.3.3.3.2. Trade

Agricultural exports accounted for around one-sixth of world agricultural production in 2012, while this proportion was higher for some commodities such as oilseeds, sugar, and fish (OECD and FAO, 2013). Global agricultural exports grew at an average annual rate of 9% in 2000–2005 and 11% in 2005–2011 (WTO, 2013, pp. 63–72). Apart from a major price hike and high price volatility since 2007–2008, several structural and cyclical factors—such as droughts in major producers, expansion of area under biofuel crop production, financial speculation, export restrictions—have led to volatility and unpredictability in the trading environment (Chapter 7; see also Abbott, 2008; FAO, 2008; Cooke and Robles, 2009; Karapinar and Haberli, 2010; Schmidhuber and Matuschke, 2010; Timmer, 2010; Headey, 2011;Wright, B.D., 2011; Anderson and Nelgen, 2012; Nazlioglu, 2013). In the absence of

extensive literature and reliable data on within-country trade, this section focuses on international trade in the specific context of climate change.

There is *limited evidence* and *medium agreement* that climate change will affect trade patterns and it will increase international trade volumes in both physical and value terms by altering the comparative advantage of countries and regions, and given its potential impacts on agricultural prices (Nelson et al., 2009b, 2010, 2013; Tamiotti et al., 2009). For example, simulation based results from variants of the National Center for Atmospheric Research (NCAR) and Commonwealth Scientific and Industrial Research Organisation (CSIRO) climate models (A2 scenario) suggest that climate change might lead to increases in export volumes (of rice, wheat, maize, millet, sorghum, and other grains) from developed to developing countries by 0.9 million Mtonnes to 39.9 million Mtonnes by 2050. Higher export volumes are expected if future scenarios consider CO_2 fertilization effects, as they produce lower world prices than scenarios without CO_2 effects. Many regions including South Asia, East Asia and Pacific, Middle East, North Africa, and sub-Saharan Africa are projected to increase their imports substantially over this period (Nelson et al., 2009b, 2010).

The recent literature highlights the potential role of trade in adaptation to climate impacts on global crop yields, while cautioning policy makers about the possible negative consequences of increased trade (Verburg et al., 2009; Lotze-Campen et al., 2010; Huang et al., 2011; Schmitz et al., 2012). Importing food might help countries adjust to climate change-induced domestic productivity shocks and mitigate related welfare losses (Reimer and Li, 2009; Tamiotti et al., 2009). Countries might also capitalize on new export opportunities arising from higher achievable yields, for example in Argentina (Asseng et al., 2013), or increasing heterogeneity of climate impacts on yields in neighboring countries, for example in Tanzania (Ahmed et al., 2012). Increased trade would lower the cost of food and thus help alleviate food insecurity; however, if it is driven by an expansion of agricultural areas (especially to marginal land and to forests), it would also lead to negative environmental consequences in the form of loss of biodiversity, deforestation, and additional carbon emissions (Verburg et al., 2009; Lotze-Campen et al., 2010; Schmitz et al., 2012).

If climate change affects crop yields negatively, and results in increased frequency of extreme events (IPCC, 2012; see also Chapter 3), especially in low-income developing countries, the consequent short-term food deficits might need to be supplied, fully or partly, through food aid (Alderman, 2010). Hence food aid agencies, such as the United Nations World Food Programme, might face additional operational challenges (Barrett and Maxwell, 2006; Harvey et al., 2010). Local or regional procurement of food aid, targeted distribution of food, and safety net programs through direct income transfers could be part of an overall strategy to address climate-induced shocks to food security (see also Chapter 7) (Alderman, 2010; Harvey et al., 2010).

The potential impacts of climate change on agricultural trade and the role that trade could play in adaptation will inevitably depend on countries' trade policies. There is *medium evidence* and *medium agreement* that deepening agricultural markets through trade reform, improved market access, avoiding export controls, and developing institutional mechanisms to improve the predictability and the reliability of the world trading system as well as investing in additional supply capacity of small-scale farms in developing countries could help reduce market volatility and offset supply shortages that might be caused by climate change (Reimer and Li, 2009; Tamiotti et al., 2009; UNEP, 2009; Karapinar, 2011, 2012; Tanaka and Hosoe, 2011; Ahmed et al., 2012).

9.3.3.3.3. Investment

Climate change may also affect investment patterns in rural areas. On the one hand, countries, regions, and sectors that are expected to be affected adversely by climate change may have difficulty attracting investment. On the other hand, ecological zones that will become favorable as a result of climate change are expected to see increasing inflow of investment. The recent price hikes in agricultural commodities have led to new initiatives of foreign direct investment (FDI) in large-scale crop production (World Bank, 2010b; Anseeuw et al., 2012), with capital-endowed countries with high food imports investing in large production projects in low-income countries endowed with low-cost labor forces and land and water resources. Climate change will lead to similar investment patterns. However, there is a risk that these new investments might not be integrated into local structures and that local populations will become increasingly vulnerable as they lose access to vital assets such as land and water (Anseeuw et al., 2012).

9.3.3.3.4. Knowledge

Rural areas are increasingly exposed to diffusion of knowledge through migration, trade and investment flows, technology transfers, and improved communication and transport facilities (IFAD, 2010), although differentials on knowledge access and diffusion (e.g., access to high-speed Internet) between rural and urban areas remain, even in high-income countries. Future impacts of climate change on these channels of integration will affect the pace and intensity of knowledge transfers. If trade, migration, and investment flows will be intensified as a result of climate change, this will have a positive impact on knowledge transfer both from and to rural areas.

Traditional knowledge (TK) developed to adapt to past climate variability and change can both be affected by climate change and used and transformed in adaptation (Nyong et al., 2007). Ettenger (2012) discusses how seasonal hunting camps among the Cree of Northern Quebec that were the occasion for intergenerational knowledge transfer have been disrupted by changing bird migrations, while new technologies such as the Internet, GPS, and satellite phones have been integrated into livelihood strategies. Climate change-induced migration can threaten TK transfer (Valdivia et al., 2010; Gilles et al., 2013). Disaster management by central government may undermine decentralization efforts, disfavoring TK transfer (Dekens, 2008).

9.3.3.4. Second-Order Impacts of Climate Policy

Policy responses for mitigation and adaptation affect rural people and their livelihoods and environments. Working toward increasing energy

Frequently Asked Questions

FAQ 9.2 | What will be the major climate change impacts in rural areas across the world?

The impacts of climate change on patterns of settlement, livelihoods, and incomes in rural areas will be complex and will depend on many intervening factors, so they are hard to project. These chains of impact may originate with extreme events such as floods and storms, some categories of which, in some areas, are projected with *high confidence* to increase under climate change. Such extreme events will directly affect rural infrastructure and may cause loss of life. Other chains of impact will run through agriculture and the other ecosystems (rangelands, fisheries, wildlife areas) on which rural people depend. Impacts on agriculture and ecosystems may themselves stem from extreme events like heat waves or droughts, from other forms of climate variability, or from changes in mean climate conditions such as generally higher temperatures. All climate-related impacts will be mediated by the vulnerability of rural people living in poverty, isolation, or with lower literacy, and so forth, but also by factors that give rural communities resilience to climate change, such as indigenous knowledge, and networks of mutual support.

Given the strong dependence in rural areas on natural resources, the impacts of climate change on agriculture, forestry, and fishing, and thus on rural livelihoods and incomes, are *likely* to be especially serious. Secondary (manufacturing) industries in these areas, and the livelihoods and incomes that are based on them, will in turn be substantially affected. Infrastructure (e.g., roads, buildings, dams, and irrigation systems) will be affected by extreme events associated with climate change. These climate impacts may contribute to migration away from rural areas, though rural migration already exists in many different forms for many non-climate-related reasons. Some rural areas will also experience secondary impacts of climate policies—the ways in which governments and others try to reduce net greenhouse gas emissions such as encouraging the cultivation of biofuels or discouraging deforestation. These secondary impacts may be either positive (increasing employment opportunities) or negative (landscape changes, increasing conflicts for scarce resources).

supply from renewable resources may result in landscape changes (Dockerty et al., 2006; Prados 2010); increasing employment opportunities (del Río and Burguillo, 2008); or increasing conflicts for scarce resources, such as water (Gold and Bass, 2010; Blair et al., 2011; McIntyre and Duane, 2011; Phadke, 2011). Planning applications for wind energy schemes in the UK have been subject to local opposition when they are perceived as having negative impacts on rural landscape qualities (van der Horst, 2007; Wolsink, 2007; Jones and Eiser, 2010). Governance of energy distribution is thus an important issue (Vermeylen, 2010; Devine-Wright, 2011). Steps toward energy self-sufficiency can reinforce rural autonomy in isolated rural communities, including indigenous groups (Love and Garwood, 2011).

Social responses to such changes are expected (Molnar, 2010). The promotion of biofuel crops has been an extremely controversial issue during 2000–2010, as they have potential socioeconomic impacts related to their asserted ability to act as stimulus for rural economies, promote changes in land ownership, and affect food security (German et al., 2011). Delucchi (2010) concludes that biofuels produced from intensive agriculture will aggravate stresses on water supplies, water quality, and land use, and impact rural areas (through land use change) and agriculture (see also Box CC-WE). Concerns about the impact of biofuel production on food security relates to increases in food prices, land concentration (and landgrabs), and competition for water (Eide, 2008; Müller et al., 2008; German et al., 2011). Gurgel et al. (2007), who modeled potential production and implications of a global biofuels industry by the end of the century under a reference scenario and a high-mitigation scenario, recognized the need for a high land conversion rate to achieve moderate objectives. Delucchi (2010) suggests developing biofuels programs with low inputs of fossil fuels and chemicals, that do not require irrigation, and on land with little or no economic or ecological opportunity cost (Plevin et al., 2010). This implies analyzing each case in its context, including production for both local and global markets, and factoring in concerns for social, cultural, and economic costs of biofuel production (i.e., impact of biofuel production on indigenous livelihoods and culture).

International mechanisms for emission reduction through forest and land management have been developed under the global initiative Reducing Emissions from Deforestation and Forest Degradation (REDD), now REDD+. These mechanisms are designed to use market tools (e.g., payment for ecosystem services) to reduce emissions, while providing social co-benefits following the principles of effectiveness, efficiency, and equity (Brown, D. et al., 2008; Hall, 2012; Hoang et al., 2013). However, there have been many criticisms that the rural poor are excluded from participation (Campbell, 2009; Sikor et al., 2010; van Noordwijk et al., 2010; Hall, 2012); and that lack of community participation can undermine a general decentralization of forest management (Phelps et al., 2010).

9.3.4. Valuation of Climate Impacts

This section assesses studies that have adopted various economic methods for valuation of impacts of climate change on rural areas. This is a difficult task and should reflect the significance of the ecological service categories for different stakeholders, including women (Kennet, 2009) and minority groups, and ideally the valuations of unit changes

in the levels of those services across management options. Valuations can be made at individual or communal levels (Farber et al., 2006) and often involve complexities with regard to the use of social discount rates for comparing intergenerational effects over varying time horizons (Dasgupta, 2011). Different understandings of value, and different philosophical approaches to address it, may exist (Weisbach and Sunstein, 2008; Kosoy and Corbera, 2010; Spangenberg and Settele, 2010), which makes it more difficult to agree on valuation methodologies. The impacts of climate change are expected to be unequally distributed across the globe, with developing countries at a disadvantage, given their geographical position, low adaptive capacities (Stern, 2007; World Bank, 2010a) and the significance of agriculture and natural resources to the economies and people (Collier et al., 2008; World Bank, 2010a). Both direct and indirect impacts have been projected, such as lower agricultural productivity, increase in prices for major crops, and rise in poverty (Hertel et al., 2010), which have implications for rural areas and rural communities. This section discusses the valuation of impacts with reference to agriculture, fisheries and livestock, water resources, mining, extreme weather events and sea level rise, recreation, tourism, and forestry. There are various channels through which changes in economic values may occur in rural areas, such as through changes in profitability, crop and land values, and loss of livelihoods of specific communities through changes in fisheries and tourism values. Losses and gains in health status and nutrition, and wider economy-wide impacts such as changes in job availability and urbanization, also impact economic values that accrue to rural communities, the opportunities and the constraints that rural communities experience, and changes that rural landscapes undergo. Because rural areas are included, but not exclusively dealt with in calculations of economy-wide gross domestic product (GDP) losses due to climate change impacts, these are not dealt with separately in this chapter. Studies on the health impacts of climate change for the most part do not distinguish between rural and urban areas, although there are specific vulnerabilities that communities in rural areas face arising from a variety of factors such as remoteness, lack of access to services, and dependence on certain occupations such as farming which are dealt with in Section 11.3. The impact on availability of freshwater resources is another major area of concern for the developing regions in particular. Climate change can adversely impact poverty through multiple channels (Sections 10.9, 13.2).

Viewing impacts regionally, despite the ongoing debates around the uncertainty and limitations of valuation studies, scholars generally agree that some African countries could experience relatively high losses compared to countries in other regions (Collier et al., 2008; Watkiss et al., 2010; World Bank, 2010a). These conclusions emerge across a range of climate scenarios and models used by researchers. For instance, Watkiss et al. (2010) use the FUND model for a business-as-usual scenario and a scenario of mitigation to 450 ppm and 2°C global mean temperature increase as generated by the PAGE2002 model, while the World Bank uses a range of country specific models for calculating costs. Global costs including adaptation costs are calculated for an approximately 2°C warmer world by 2050 for Mozambique, Ethiopia, Ghana, Bolivia, Vietnam, Samoa, and Bangladesh. Overall negative consequences are seen for Africa and Asia, due to changes in rainfall patterns and increases in temperature (Müller et al., 2011). Though climate change and climate variability would impact a range of sectors, water and agriculture are expected to be the two most sensitive to climatic changes in Asia (Cruz et al., 2007; see also Chapter 3) and for droughts in particular for Australia (Meinke and Stone, 2005; Nelson et al., 2007). In Latin American and Caribbean countries, higher temperatures and changes in precipitation patterns associated with climate change affect the process of land degradation, compromising extensive agricultural areas. Research on climate change impacts in rural North America has largely focused on the effects on agricultural production and on indigenous populations, many of whom rely directly on natural resources. Developed countries in Europe will be less affected than the developing world (Tol et al., 2004), with most of the climate sensitive sectors located in rural areas.

Valuation and costing of climate impacts draw upon both monetary and non-monetary metrics. Most studies use models that estimate aggregated costs or benefits from impacts to entire economies, or to a few sectors, expressed in relation to a country's GDP (Stage, 2010; Watkiss, 2011). Values that are aggregated across sectors generalize across multiple contexts and could mask particular circumstances that could be significant to specific locations, while expressing outcomes in aggregated GDP terms. This is a matter of concern for economies in Africa and Asia, where subsistence production continues to play a key role in rural livelihoods. Valuation of non-marketed ecosystem services poses further methodological and empirical concerns (Dasgupta, 2008, 2009; Stage, 2010; Watkiss, 2011). Würtenberger et al. (2006) developed a methodology to estimate environmental and socioeconomic impacts of agricultural trade regarding virtual land use, and Adger et al. (2011) use qualitative methodologies to consider non-market metrics of risk, focusing on place- and identity-based principles of justice, which recognize individual and community identity in decision making.

Integrated assessment models and cost-benefit tools have been criticized: for being inadequate to assess intergenerational events, or processes with high levels of uncertainty and irreversibility; for not considering equity concerns and power structures; for assigning monetary values on the basis of incomplete information or assuming speculative judgments regarding the monetary value of, for example, natural resources (Kuik et al., 2008; Ackerman et al., 2009); and for not recognizing incommensurability (Aldred, 2012). In recent years, various perspectives for valuing the economic impacts of climate change have come into focus including the feminist (Nelson, 2008; Power, 2009), deliberative (Zografos and Howarth, 2010), or behavioral economics-based (Brekke and Johansson-Stenman, 2008; Gowdy, 2008), and the integration of economics with moral and political philosophy (Dietz et al., 2008). Some common characteristics of these new approaches include interdisciplinarity, acknowledging the diversity of views, and maintaining complexity in models. Research in this area, although relatively recent, shows promise. Illustrative regional and sub-regional estimates for the value of agricultural and non-agricultural impacts of climate change, as available in the literature, are presented here.

9.3.4.1. Agriculture

Changes in agricultural production will have corresponding impacts on incomes and well-being of rural peoples. The largest known economic impact of climate change is on agriculture because of the size and sensitivity of the sector, particularly in the developing world and to a lesser extent in parts of the developed world. A large number of studies

to evaluate the impacts on the agricultural sector and its ramifications for communities have been conducted at various scales, ranging from micro-level farm models to large-scale regional and country level climate cum socioeconomic scenario modeling exercises. Some of these also report values for associated economic losses.

Since models are simplifications of complex real-world phenomena, different models tend to highlight different aspects of impacts and their consequent economic values. For instance, in estimating economic losses the Ricardian method has been used widely to study climate change impacts (with adaptation inbuilt) in agriculture. However, often such analysis does not incorporate features like technological progress, relative price changes, agricultural policy, and other dynamic characteristics. Similarly on the biophysical impacts side, changes in the El Niño-Southern Oscillation (ENSO) statistics may also have serious economic implications for the agricultural sector in certain countries such as in Latin America and Australia (Kokic et al., 2007). However, ENSO responses differ strongly across climate models, and at the current stage of understanding do not allow conclusions to be drawn on how global warming will affect the Tropical Pacific climate system (Latif and Keenlyside, 2009). A sample of the available studies is provided in Table 9-6.

9.3.4.2. Other Rural Sectors: Water, Fisheries, Livestock, Mining

The changes in valuation of water resources due to climate change arise from expected impacts on populations dependent on these water resources and these will be felt in several parts of the world (Sections 3.4.9, 3.5, 3.8). Monetary estimates of losses due to impacts on water resources are not generalizable. Among alternative approaches to value water resources, use of the water footprint tool (Hoekstra and Mekonnen, 2012), which measures human utilization of water by a nation, and the concept of virtual water have been suggested for informing policy makers in water-scarce countries, such as Egypt.

Analysis of intergenerational valuation has provided some interesting results in valuation of marine fisheries (Ainsworth and Sumaila, 2005). For fisheries in rural coastal areas, some of the challenges faced include the valuation of environmental externalities such as breeding habitats, or mangroves, that might be lost due to climate change or other forces (Hall, 2011). It has also been argued that the true worth of livelihoods dependent on fisheries in developing countries, where these constitute part of a diversified livelihood or subsistence strategy, requires a different set of metrics from those used in the developed world (Mills et al.,

Table 9-6 | Illustrative sample of studies on economic value and changes in value from climate change impacts in the agriculture sector.

Findings and estimates	Country/region and model/scenario	Study
Annual economic loss in rice production: $54.17 million	Malaysia (2°C rise in temperature)	Vaghefi et al. (2011)
GDP reduction from loss of agricultural productivity by 2080: 1.4%; welfare loss: 1.7%	Southeast Asian countries: Thailand, Vietnam, Philippines, Singapore, Malaysia, Indonesia (dynamic CGE)	Zhai and Zhuang (2009)
Decline in food grain production between 2030 and 2050 by up to 18%	India (SRES A1B scenario)	Dasgupta et al. (2013)
Annual spending for coping with adverse agricultural impacts between 2010 and 2050: US$4.2–5 billion	Asia (various scenario based estimates)	ADB and IFPRI (2009)
Decline in farmland values for each degree Celsius of warming: 4–6000 pesos	Mexico (Ricardian analysis)	Mendelsohn et al. (2010)
Fall in crop land values for rural communities: 13%	USA (10% average increase in temperature)	Mendelsohn et al. (2007)
Mixed effects with some improved profits	Canada (increasing precipitation)	Mendelsohn and Reinsborough (2007)
Adverse impacts on farming	USA (increasing temperature)	Mendelsohn and Reinsborough (2007)
Crop losses under drought: CAN$7–171 per hectare	Canada (Canadian Global Model 2)	Wittrock et al. (2011)
Annual agricultural losses up to $3 billion Flooding increases losses	California (SRES B1 (low emissions) and SRES A2 (medium emissions) scenarios)	Franco et al. (2011)
Damages to agriculture, hydropower, and infrastructure (including coastal areas) by 2050: US$7.6 billion	Mozambique (dynamic CGE model)	World Bank (2010a)
Decline in gross domestic product (GDP) from agriculture and linked sectors: 10% from benchmark levels	Ethiopia (Cline, CGCM2, and PCM)	Mideksa (2010)
By 2100: total losses of US$48.2 billion to gains of US$90 billion In 2020 for 1.6% warmer and 3.7% drier climate: net farm revenues decline by up to 25%	11 African countries (Ricardian analysis; various climate scenarios)	Dinar et al. (2008)
Decline in daily per capita calorie availability by up to 10% in 2050	Developing countries (SRES A2 scenario; CSIRO and NCAR models)	Nelson et al. (2009)
Losses in gross value of production up to 25% (Guatemala, followed by other countries)	Guatemala, Belize, Costa Rica, Honduras (SRES A2 and B2; Regional climate models)	UN ECLAC (2010a,b)
Loss in incomes of farmers by 2020: 14%; by 2060: 20%	South America (SRES A1; Canadian Climate Centre)	Seo and Mendelsohn (2008)
Annual damages between 1% and 39% in farm property values	Brazil (climate predictions from 14 GCMs)	Sanghi and Mendelsohn (2008)
Varying impacts across regions; declining agricultural crop productivity in some	Southern Europe (IPCC AR4 climate projections; qualitative assessment)	Falloon and Betts (2010)
Large variation in impacts on crops in Europe by 2050, mostly negative	Most affected: Hungary, Serbia, Bulgaria, Romania (expert evaluation; climate predictions from RCMs)	Olesen et al. (2011)

Notes: CGCM2 = Coupled General Circulation Model 2; CGE = Computable General Equilibrium; CSIRO = Commonwealth Scientific and Industrial Research Organisation; GCM = General Circulation Model; NCAR = National Center for Atmospheric Research; RCM = Regional Climate Model; SRES = Special Report on Emission Scenarios.

2011). Climate change can also have significant impacts on livestock production (Section 9.3.3.1).

A relatively less researched area which may impact the livelihoods of rural communities is mining (Section 26.11.1.2). Economic viability of mining enterprises as well as communities dependent on them is vulnerable to climate change. Pearce et al. (2011) highlight concerns for Canada, where mining is a rural activity with few other available economic activities while Damigos (2012) finds economic losses for mining in the Mediterranean region and Greece in particular. Current and past infrastructure for mines was built under a no-climate change presumption and economic and ecological vulnerabilities as a result are substantial, and industry actors are unprepared to deal with this. There is little research on impacts in mining sectors in the USA and Mexico. Changes in the energy and water sector present a complex mix of risks and opportunities for primary extraction and processing industries. Site management, transport of supplies and resources to and from mines, exploration activities, and their associated costs would determine the extent of loss, along with the importance of the sector in the local economy (Backus et al., 2012).

9.3.4.3. Extreme Weather Events, Sea Level Rise

The climate change-related extreme events that may cause changes in economic values in rural areas include heat waves and droughts, storms, inundation, and flooding (Stern, 2007; Handmer et al., 2012; see also Section 3.4.9). A detailed discussion on the costs of climate extremes and disasters is set out by Handmer et al. (2012). Costs can be of two kinds: losses or damage costs and costs of adaptation. While some of the costs lend themselves to monetary valuation (such as infrastructure costs), others cannot be easily estimated such as the value of lives lost and the value of ecosystem services lost (for discussion on the methodologies for valuing costs refer to Handmer et al., 2012; see also Section 4.5.3).

Damage costs of floods and droughts (Section 10.3.1) and from sea level rise in Europe (Swiss Re, 2009) demonstrate the cost implications for rural communities in the developed regions of the world. Studies mapping the adverse impacts in UK and elsewhere in Europe show a range of sectors that are impacted in rural areas particularly due to drought in Europe and flooding in UK, with the worst effect being on summer crops in Mediterranean regions (Giannakopoulos et al., 2009). Longer term adaptation could reduce the severity of losses but could include displacement of agricultural and forestry production from southern Europe to the North. The UK Government's Foresight Programme (Foresight, 2004) estimates that global warming of 3°C to 4°C could increase flood damage costs from 0.1% up to 0.4% of GDP. Much of the investment in flood defenses and coastal protection would be in rural coastal areas.

Several studies from the developing countries provide evidence on the substantial costs rural communities in particular face in these countries. Salinity and salt water intrusion have implications for rural livelihoods as they impact both fisheries and agriculture (Section 5.5.3). Sea level rise also leads to wetland loss and coastal erosion. A few illustrations of the range of impacts of relevance for the rural economy are provided here. Loss of agricultural land and changes in the saline-freshwater interface is estimated to impact the economies of Africa adversely (Dasgupta, S. et al., 2009; SEI, 2009). Ahmed et al. (2009) suggest that climate volatility from increase in extreme events increases poverty in developing countries, particularly Bangladesh, Mexico, Indonesia, and countries in Africa. They also find that on simulating the effect of climate extremes on poverty in Mexico using the A2 scenario as generated by a Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model data set, rural poverty increases by 43 to 52% following a single climate shock due to climate extremes. Studying extreme events, Boyd and Ibarrarán (2009) use a CGE model to simulate the effects of persistent droughts on the Mexican economy and find declines in production of 10 to 20% across a variety of agricultural sectors between 2005 and 2026. Scenario-based stakeholder engagement has been tested for coastal management planning under climate change threats (Tompkins et al., 2008) and to determine impacts and responses of extreme events in coastal areas (Toth and Hizsnyik, 2008).

9.3.4.4. Recreation and Tourism; Forestry

Studies assessing the changes in economic value of recreation and tourism due to climate change are relatively fewer in number (coastal tourism is discussed in Section 5.4.4.2). Both sensitivity to climate variability and climate change have been considered in the literature. While some studies locate an increase in values for certain regions others estimate shifts in tourism and losses (Hamilton et al., 2005; Bigano et al., 2007; Beniston, 2010). Methodological challenges and contrasting findings for the short and long run pose problems in generalizing findings (economic values for recreation and tourism are discussed in Section 10.6). Change in economic values will impact rural communities (Lal et al., 2011), with the linkages between biodiversity, tourism, and rural livelihoods and rural landscapes being an established one both for developing and developed countries (Scott et al., 2007; Collins, 2008; Wolfsegger et al., 2008; Hein et al., 2009; Nyaupane and Poulde, 2011).

It has been argued that climate change would have adverse impacts on various ecosystems, including forests and biodiversity in many regions of the world (Preston et al., 2006; Stern, 2007; Eliasch, 2008; ADB, 2009; Ogawa-Onishi et al., 2010; Tran et al., 2010) and these will have implications for rural livelihoods and economies (Fleischer and Sternberg, 2006; Safranyik and Wilson, 2006; Chopra and Dasgupta, 2008; Kurz et al., 2008; Walton, 2010). However, monetary valuation of changes in non-marketed ecosystem services due to climate change continues to pose a challenge to researchers. To overcome some of the limitations, multi-criteria analysis has been used for forest management (Fürstenau et al., 2007).

9.3.5. Key Vulnerabilities and Risks

9.3.5.1. Drivers of Vulnerability and Risk

Discussions on climate vulnerability in rural areas must recognize competing conceptualizations and terminologies of vulnerability, particularly those of "starting point" and "end-point" vulnerability (O'Brien et al., 2007). The focus here is on starting point vulnerability,

or contextual vulnerability (see Glossary and Chapter 19), while we consider risk to be the probability of adverse impact resulting from exposure and vulnerability (see Chapter 19). These distinctions are important because they can result in contradictory findings regarding vulnerability in rural areas, and the policy prescriptions derived therefrom are also different.

There is *low agreement*, but *medium evidence*, on the direction in which some key factors may affect vulnerability or resilience in rural areas, including rainfed as opposed to irrigated agriculture, small-scale and family-managed farms, integration into world markets, and diversification. Brouwer et al. (2007), contrary to expectations, found that vulnerability to flooding in Bangladesh in terms of damage suffered was lower for households that fully depended on natural resources than those who did not. Osbahr et al. (2008) found that diversification in rural areas does not always reduce vulnerability and can increase inequity within communities if it is not accompanied by reciprocity. There is *robust evidence* and *high agreement* on the importance for resilience of drivers such as access to land and natural resources, flexible local institutions and knowledge and information, and the association of gender and vulnerability (see Box CC-GC and Chapter 13).

The most commonly used approaches to analyzing causes of vulnerability use the concepts of entitlements or livelihoods in evaluating the multi-scale factors shaping people's assets, as well as their adaptive capacity to hazards and stressors. Although vulnerability is experienced locally, its causes and solutions occur at different social, geographic, and temporal scales, and are seen as context dependent (Ribot, 2010). Non-climate factors affecting vulnerability in rural areas at both individual and community levels (Eakin and Wehbe, 2009) include the following:

- Physical geography, for example, desert or semi-desert conditions (Lioubimtseva and Henebry, 2009), remoteness (Horton et al., 2010), level of dependence on climate conditions (Brondizio and Moran, 2008; Sietz et al., 2011)
- Economic constraints and poverty (Macdonald et al., 2009; Mertz et al., 2009a; Ahmed et al., 2011; Sietz et al., 2011)
- Gender inequalities (Nelson et al., 2002)
- Social, economic, and institutional shocks/trends (e.g., urbanization, industrialization, prevalence of female-headed households, landlessness, short-time policy horizons, low literacy, high share of agriculture in GDP), as well as demographic changes, HIV/AIDS, access to and availability of food, density of social networks, memories of past climate variations, knowledge, and long-term residence in the region (Parks and Roberts, 2006; Brondizio and Moran, 2008; Cooper et al., 2008; Macdonald et al., 2009; Mertz et al., 2009a; Simelton et al., 2009; Gbetibouo et al., 2010b; Ruel et al., 2010; Sallu et al., 2010; Ahmed et al., 2011; Mougou et al., 2011; Seto 2011).

This section focuses on the following drivers of vulnerability to climate change: water, market orientation and farm scale, institutions and access to resources, gender, migration, and access to information and knowledge.

9.3.5.1.1. Access to water

Reducing vulnerability requires a reduction of the multiple non-climate-related pressures on freshwater resources (e.g., water pollution, high water withdrawals) together with improvement of water supply and sanitation in developing countries (Kundzewicz et al., 2008). Water supply will be adversely affected by climate change, but vulnerability of populations will also be determined by other elements, such as the role of institutions in facilitating the access to water, or people's demand, which in turn is influenced by local cultural norms (Wutich et al., 2012) and perceptions of vulnerability which may differ between men and women (Larson et al., 2011). Improvements in technologies can reduce the perception of water scarcity and increase water demand without reductions in underlying vulnerability (El-Sadek, 2010; Sowers et al., 2011). Where appropriate water management institutions exist and are effective, their role in improving rural livelihoods has been demonstrated, for example in Tanzania's Great Ruaha basin (Kashaigili et al., 2009).

Past research has tended to agree that rainfed agriculture is more vulnerable to climate change (Bellon et al., 2011) and that irrigation is needed to decrease that vulnerability (Gbetibouo et al., 2010a). More recent findings suggest that this is context dependent and irrigation has been found to increase vulnerability in certain cases (Eakin, 2005; Lioubimtseva and Henebry, 2009). Cooper et al. (2008) concluded that in rainfed sub-Saharan Africa the focus should be on improving productivity of rainfed agriculture instead of irrigation as irrigation schemes are also being threatened by drought, and Ahmed et al. (2011) emphasize the role of drought-tolerant crops.

9.3.5.1.2. Market orientation and farm scale

Some authors argue that opening markets to international trade increases vulnerability of small farmers and poor people. However, linkages among international, regional, and local markets are not clear, including how global prices affect regional and local prices in the long term (Ulimwengu et al., 2009). Market integration is seen as reducing the capacity of indigenous or smallholder systems for dealing with climate risk in Bolivia (Valdivia et al., 2010), Honduras (McSweeney and Coomes, 2011), Mexico (Eakin, 2005), Mozambique (Eriksen and Silva, 2009; Silva et al., 2010), and in the Sahel (Fraser et al., 2011) by variously accelerating socioeconomic stratification and reducing crop diversity. On the other hand, distance from large markets is seen as increasing vulnerability of rainfed mixed crop/livestock areas in sub-Saharan Africa (Jones and Thornton, 2009) and the Peruvian Altiplano (Sietz et al., 2011). Each case needs to be analyzed within its complexity, considering interactions among all the factors that can affect vulnerability (Rivera-Ferre et al., 2013a).

Regarding the scale of farms, some authors suggest that small-scale farming increases the vulnerability of communities in rural areas (Gbetibouo et al., 2010b; Bellon et al., 2011) although their resilience (stemming from factors such as indigenous knowledge, family labor, livelihood diversification) should not be underestimated. Brondizio and Moran (2008) indicate that small farmers are less vulnerable than large, monocrop farmers when climatic variations make an area inappropriate for a particular crop, because they tend to cultivate multiple crops and work with on-farm biodiversity. However, they recognize that small farmers tend to suffer from technological limitations, low access to extension services, and market disadvantages.

9.3.5.1.3. Institutions, access to resources, and governance

Institutions and networks can affect vulnerability to climate change: through distribution of climate risks between social groups; by determining the incentive structures for adaptation responses; and by mediating external interventions (e.g., finances, knowledge and information, skills training) into local contexts (Agrawal and Perrin, 2008; Ribot, 2010). Institutions can decrease vulnerability (Anderson et al., 2010) or increase it (Eakin, 2005). Governance structures and communication flows as shown in a Swiss mountain region vulnerable to climate change (Ingold et al., 2010) and the knowledge and perceptions of decision makers are also important. Romsdahl et al. (2013) show that local government decision makers in the U.S. Great Plains resist seeing climate change as within their responsibilities, which has contributed to low levels of planning for either adaptation or mitigation, and thus to greater vulnerability, but that a reframing of issues around current resource management priorities could allow proactive planning.

Lack of access to assets, of which land is an important one, is accepted to be an important factor increasing vulnerability in rural people (McSweeney and Coomes, 2011). The breakdown of traditional land tenure systems increases vulnerability, particularly for those who experience poorer land access as a result (Brouwer et al., 2007; Dougill et al., 2010; Fraser et al., 2011). Those who benefit, for example, wealthier farmers who increased their landholding after privatization in Botswana, remain less vulnerable (Dougill et al., 2010).

9.3.5.1.4. Migration

The relationship of vulnerability to migration is complex. Areas of out-migration can experience reduced vulnerability if migrants send remittances, or increased vulnerability if the burden of work, usually for women, also increases. The decline in transmission of traditional knowledge through social networks can also increase vulnerability (Valdivia et al., 2010). Furthermore, those places receiving migrants can experience an excessive demographic growth, which increases pressure over scarce resources, as is being experienced in the semiarid tropics (Cooper et al., 2008; Obioha, 2008). Brondizio and Moran (2008) found that in-migration in the Amazon brought people with knowledge that is ill-adapted to the local environment (see Section 12.4).

9.3.5.1.5. Gender

Box CC-GC sets out the general issues on climate change and gender-related inequalities. These are of special relevance to rural areas, particularly but not solely in the developing world (Nelson and Stathers, 2009; Vincent et al., 2010; Alston, 2011) (*robust evidence*, *high agreement*). Access to land shows strong differences between men and women, as do labor markets (FAO, 2010), and access to non-farm entrepreneurship (Rijkers and Costa, 2012). Fewer than 20% of the world's landholders are women, but women still play a disproportionate role in agriculture. On average women make up around 43% of the agricultural labor force in developing countries; in South Asia almost 70% of employed women work in agriculture, and more than 60% in sub-Saharan Africa (FAO, 2010, 2011). Climate change also increases vulnerability through male out-migration that increases the work to women (Chindarkar, 2012); cropping and livestock changes that affect gender division of labor (Lambrou and Paina, 2006); increased difficulty in accessing resources (fuelwood and water) (Tandon, 2007); and increased conflicts over natural resources (Omolo, 2011).

Women are generally, though not in every context, more vulnerable to the impacts of extreme events, such as floods and tropical cyclones (Neumayer and Plümper, 2007).

9.3.5.1.6. Knowledge and information

Lack of access to information and knowledge of rural people can also interact with all the above mentioned drivers to mediate vulnerability. Shared knowledge and lessons learned from previous climatic stresses provide vital entry points for social learning and enhanced adaptive capacity (Tschakert, 2007). But while some authors emphasize the need for local responses and indigenous knowledge to reduce vulnerability (Valdivia et al., 2010), and call for an integration of local knowledge into climate policies (Nyong et al., 2007; Brugger and Crimmins, 2012), Bellon et al. (2011) state that local knowledge is too local, and in some contexts gathering information from further away is important.

Access to information alone is not a guarantee of success. Coles and Scott (2009) found that in Arizona, despite ample access to weather forecasting, ranchers did not rely on such information, implying that changes are required to make more attractive information to users, as well as to understand prevailing local cultures and norms.

It is also important how knowledge is produced, managed, and disseminated within the formal institutional structure to address vulnerability issues. A local case study in Sweden shows that limited cooperation between local sector organizations, lack of local coordination, and an absence of methods and traditions to build institutional knowledge present barriers to manage vulnerability (Glaas et al., 2010). In Benin, as elsewhere in Africa, there is a lack of coordination between climate policies and the policies and practices that govern agricultural research and extension, while good practice at project level has been insufficiently harnessed to foster collective learning of farmers and other agricultural stakeholders, and thus adaptation to climate change (Moumouni and Idrissou, 2013a,b). For institutional learning, knowledge transfer, and more reliable assessments of local vulnerabilities, local institutional structure must be flexible, establishing communication mechanisms among public authorities, other knowledge producers, and civil society (Glaas et al., 2010).

9.3.5.2. Outcomes

The outcome of vulnerability is the result of, and interaction of, the driving forces that determine vulnerability in a given sector, social group, and so forth. This section analyzes how different drivers may affect specific vulnerable groups in rural areas, particularly pastoralists, mountain farmers, and artisanal fisherfolk. Box 9-2 takes a specific economic sector important in rural areas and demonstrates the interplay of vulnerability and exposure.

Box 9-2 | Tourism and Rural Areas

The three major market segments of tourism most liable to be affected by climate change are rural-based, namely, coastal tourism, nature-based tourism, and winter sports tourism (Scott et al., 2012). Tourism is a significant rural land use in many parts of the world, yet compared to other economic sectors in rural areas, the impacts of climate change are typically under-researched. In the Caribbean, for example, tourism has overtaken agriculture in terms of economic importance, with several regional states (including the Bahamas, the Cayman Islands, and St Lucia) receiving more than 60% of their GDP from this industry (Meyer, 2006). Coastal environments elsewhere in the world are also characterized by dependence on rural tourism, and are known to be vulnerable to cyclones and sea level rise (Payet, 2007; Klint et al., 2012a).

Terrestrial natural resource-based tourism is also a significant foreign exchange earner in many countries. In sub-Saharan Africa, between 25 and 40% of mammal species in national parks are *likely* to become endangered by 2080, assuming no species migration (and 10 to 20% with the opportunity for migration) (Thuiller et al., 2006). There are also many rural environments viewed as "iconic" or having cultural significance that are vulnerable to climate change. In South Africa, for example, the Cape Floral (fynbos) ecosystem has a high level of species endemism which will be vulnerable to the projected increase in dry conditions (Midgley et al., 2002; Boko et al., 2007). The projected increase in climate change-related hazards, such as glacial lake outbursts, landslides, debris flows, and floods, may affect trekking in the Nepali Himalayas (Nyaupane and Chhetri, 2009).

The development of tourism has, in many cases, increased levels of exposure to climate change impacts. In the Caribbean, for example, tourism has led to considerable coastal development in the region (Potter, 2000), which may exacerbate vulnerability to sea level rise. In many cases, the carbon emissions resulting from participating in rural tourism threaten the very survival of the areas being visited. This is often the case for very remote locations, for example, polar bear tourism in Canada (Dawson et al., 2010), and dive tourism in Vanuatu (Klint et al., 2012b). Although on aggregate resource consumption of tourists and locals has been shown to be similar in developed county contexts (e.g., in Italy; Patterson et al., 2007); in many developing countries resource use by tourists is much higher than that of locals (e.g., in Nepal; Nepal, 2008).

Despite the potential impacts of climate change on rural tourism, there is *low evidence* of significant concern, which impedes adaptive responses. Surveys in both the upper Norrland area of northern Sweden and New Zealand showed that climate change is not perceived to pose a major threat in the short term, relative to other business risks perceived by small business owners and tourism operators (Hall, 2006; Brouder and Landmark, 2011).

That said, there is evidence that, with planned adaptation, tourism can flourish in rural areas under climate change. In the Costa Brava region of Spain, for example, although the increasing temperatures and reduced water availability are projected to negatively impact tourism in the current high seasons, there is scope to shift to the current shoulder seasons, namely April, May, September, and October (Ribas et al., 2010). Recognition of the opportunities for adaptation has also necessitated reassessment of the extent of the potential impacts of climate change on the tourism industry in rural areas. With the availability of snowmaking as a (costly and uncertain) adaptation in the eastern North American ski industry, only 4 out of 14 ski areas are at risk before 2029, but 10 out of 14 in the period 2070–2099 (Scott et al., 2006).

9.3.5.2.1. Pastoralists

Pastoralists have developed successful strategies for responding to climate variability, especially "strategic mobility" in pursuit of high-quality grazing (Krätli et al., 2013), in combination with shorter-term coping strategies (Morton, 2006), for example, in sub-Saharan Africa (Davies and Bennett, 2007; Kristjanson et al., 2010) or Inner Mongolia (Wang and Zhang, 2012). However, mobility, a key component for community resilience, is declining , increasing the vulnerability of people in arid and semiarid regions (Lioubimtseva and Henebry, 2009; Fraser et al., 2011). The lack of other alternatives in certain marginal areas where animals are the only secure assets can lead to overstocking and overgrazing, and thus to increased vulnerability of pastoralism (Cooper et al., 2008).

This is "induced vulnerability" (Krätli et al., 2013), arising from a range of social, economic, environmental, and political pressures external to pastoralism that bring about encroachment on rangelands; inappropriate land policy; undermining of pastoral culture and values; and economic policies promoting uniformity and competition over diversity and complementarity. Other authors list as constituents of increased vulnerability: population growth; increased conflict over natural resources; changed market conditions and access to services under liberalization; concentration of political power in national centers; and perceptions that pastoralists are backward (Smucker and Wisner, 2008; Dougill et al., 2010; Dong et al., 2011; Rivera-Ferre and López-i-Gelats, 2012). These in turn can be seen as results of what Reynolds et al. (2007) conceptualize as two key features of dryland populations: remoteness, and distance from the centers and priorities of decision makers or "distant voice." However, Dong et al. (2011) and Sietz et al. (2011) stress the geographic differentiation of pastoral systems (and more broadly of dryland systems).

9.3.5.2.2. Mountain farmers

Mountain ecosystems have been identified as extremely vulnerable to climate change (Fischlin et al., 2007), and thus populations have a high exposure to climate change. A detailed understanding of climate change impacts in mountain areas is difficult because of physical inaccessibility and scarcity of resources for research in mountain states and regions (Singh et al., 2011), as well as more generic uncertainties relating to climate projection.

Mountain dwellers, as pastoralists in drylands, are adapted to live in steep and harsh and variable conditions, and thus have a variety of strategies to adapt and foster resilience to changing climatic conditions. However, to develop their strategies they need to overcome other drivers that can affect their vulnerability in different contexts. For instance, in most developed countries, mountains are becoming depopulated (Gehrig-Fasel et al., 2007; Gellrich et al., 2007; López-i-Gelats, 2013) given the extreme climatic conditions and their remoteness and subsequent isolation, while in developing countries (e.g., tropical mountain areas) there is a trend toward increasing population (Huber et al., 2005; Lama and Devkota, 2009). The impacts of the projected warming on mountain farming, as well as their adaptation strategies, differ spatially because the socioeconomic role of mountains varies significantly between industrialized and industrializing or non-industrialized countries (Nogués-Bravo et al., 2007). Mountain grasslands in developed countries are usually managed via a sub-exploitation model that involves the intensive use of the most productive areas and the abandonment of those regions where production is economically less viable (López-i-Gelats et al., 2011). In contrast, mountain grasslands in developing countries remain centers of fodder and livestock production. Thus, two general trends are identified in world mountain grasslands: while temperate mountain grasslands tend to suffer from conversion to agriculture, and land abandonment where livestock raising is less feasible (Gellrich et al., 2008), in tropical mountain grasslands the main cause of degradation is overgrazing, linked to processes of demographic growth. Land privatization, loss of grazing rights, or changes in land use (e.g., development of infrastructure) also affect mountain farmers both in developed and developing countries (Tyler et al., 2007; Xu et al., 2008).

9.3.5.2.3. Artisanal fisherfolk

Small coastal and riparian rural communities face several drivers that increase their vulnerability, which remain largely ignored by mainstream fisheries policy analysts; for example, the potential impact of demographic, health, and disease trends, or of wider development policy trends (Hall, 2011); pressure from other resources (e.g., water, agriculture, coastal defense); unbalanced property rights; and lack of adequate health systems, potable water, or sewage and drainage (Badjeck et al., 2010). The most important drivers affecting small-scale fisheries can be grouped into international trade and globalization of markets; technology; climate and environment; health and disease; demography; and development patterns and aquaculture. For instance, freshwater fisheries are threatened by increasing irrigation, while vulnerability of coastal fisheries increases with mangrove loss to aquaculture facilities in response to growing markets for prawns (Hall, 2011). Another difficulty faced by fisheries-based livelihoods is the neglect of governments and researchers, which is more focused on industrial fishing than artisanal fishing (Mills et al., 2011).

9.4. Adaptation and Managing Risks

9.4.1. Framing Adaptation

AR4 stated with *very high confidence* that adaptation to climate change was already taking place, but on a limited basis, and more so in developed than developing countries. Since then, the documentation of adaptation in developing countries has grown (*high confidence*). Adaptation is progressive, and is distinguished from coping as it reduces vulnerability in the case of re-exposure to the same hazard (Vincent et al., 2013): it can therefore be identified even without *high confidence* that a local hazard or climate trend is attributable to global climate change—indeed many cases of adaptation are driven primarily by other stressors, but have the result of aiding adaptation to climate change (Berrang-Ford et al., 2011).

Many adaptations do build on examples of responses to past variability in resource availability, and it has been suggested that the ability to cope with current climate variability is a prerequisite for adapting to future change (Cooper et al., 2008). At the same time, however, it cannot be assumed that past response strategies will be sufficient to deal with the range of projected climate change. In some cases, existing coping strategies may increase vulnerability to future climate change, by prioritizing short-term resource availability (Adepetu and Berthe, 2007; O'Brien et al., 2007). In Malawi, for example, forest resources are used for coping (gathering wild food and firewood to sell), but this process reduces the natural resource base and increases vulnerability to future flooding through reduced land cover and increased overland flow (Fisher et al., 2010). In developing countries, there is *high confidence* that adaptation could be linked to other development initiatives aiming for poverty reduction or improvement of rural areas (Eriksen and O'Brien, 2007; Hassan, 2010; Nielsen et al., 2012; see also Section 13.4). For more information on the integration of adaptation and development in climate-resilient development pathways, see Chapter 20. In Ethiopia, for example, "low regrets" measures to respond to current variability are important to shift the trajectory from disaster-focused to longer-term vulnerability reduction (Conway and Schipper, 2011).

9.4.2. Decision Making for Adaptation

Decision making for adaptation takes place at a variety of levels, and can be public or private. International mechanisms variously support adaptation decision making at all levels (see Sections 14.4, 15.2). At the national and local levels, law and policies can enable planned adaptation (Stuart-Hill and Schulze, 2010). A longer history of evidence for public policies to support adaptation exists for developed countries, although increasingly developing countries are also introducing such policies (for more information, see Section 15.2, Box 25-2 on Australia's water policy and management, and Section 26.9.1 on federal adaptation policies in the USA and Canada). At local levels, some progress toward adaptation planning has been observed, particularly in developed countries. In Australia, for example, western Australia, South Australia, and Victoria have mandatory State planning benchmarks for 2100 (see Box 25-1) and, in the Great Plains of the USA, some jurisdictions have developed plans on either climate adaptation or climate mitigation, although so far fewer than 20% have done so (Romsdahl et al., 2013). At the local level, many adaptations are examples of private decisions for adaptation, undertaken by NGOs (primarily in developing countries, often in the form of community-based adaptation), and companies and individuals. Public and private decision making for adaptation is not always mutually exclusive: one example of where policy can support private adaptation is in the provision of index-based insurance schemes (Linnerooth-Bayer and Mechler, 2007; Suarez and Linnerooth-Bayer, 2010), which have variously been trialed in India, Africa, and South America (Patt et al., 2009, 2010; for a case study on index-based weather insurance in Africa, see Box 22-1). However, national policies and laws are not always mutually supportive of private actions (Stringer et al., 2009).

There is now *high confidence* that public decision making for adaptation can be strengthened by understanding the decision making of rural people in context, and in particular considering examples of autonomous adaptation and the interplay between informal and formal institutions (Bryan et al., 2009; Eakin and Patt, 2011; Adhikari and Taylor, 2012; Naess, 2012). Adaptation can also build upon local and indigenous knowledge for responding to weather events and a changing climate as has been observed in Samoa (Lefale, 2010; see Chapter 29), the Solomon Islands (Rasmussen et al., 2009; see Chapter 29), Namibia (Newsham and Thomas, 2011), Canada (Nakashima et al., 2011; see Chapter 24), the Indo-Gangetic Plains (Rivera-Ferre et al., 2013b), and Australia (Green et al., 2010).

9.4.3. Practical Experiences of Adaptation in Rural Areas

In AR4, examples of adaptation in rural areas exhibited a bias toward developed countries (WGII AR4 Chapter 17), but since then practical examples of adaptation in rural areas have increased substantially in developing countries (*very high confidence*). These practical experiences of adaptation are found in agriculture, water, forestry and biodiversity, and fisheries.

9.4.3.1. Agriculture

Agricultural societies have a history of responding to the impacts of change in exogenous factors, including (but not limited to) weather and climate (Mertz et al., 2009a). They undertake a range of adjustment measures relating to their farming practices—for example, planting, harvesting, and watering/fertilizing existing crops; using different varieties; diversifying crops; and implementing management practices such as shading and conservation agriculture. Table 9-7 gives some examples; Box 9-3 describes adaptation initiatives in the beverage crop sector. More information on agricultural adaptation is available in Sections 23.8.2 (Europe), 24.4.3.5 (Asia), 25.7.2 (Australasia), 26.5.4 (North America), and 27.3.4.2 (Central and South America).

Conservation agriculture shows promising results and can be used as an adaptation (Speranza, 2013) and for sustainable intensification of production (Pretty et al., 2011), with significant yield productions observed in South Asia and southern Africa (Erenstein et al., 2012). See Box 22-2 for a case study on integrating trees into annual cropping systems. Water management for agriculture is also critical in rural areas under climate change, for example, the use of rainwater harvesting (Vohland and Barry, 2009; Kahinda et al., 2010; Rivera-Ferre et al., 2013b), and more efficient irrigation, particularly in rural drylands (Thomas, 2008).

Adaptations are also evident among small-scale livestock farmers (Kabubo-Mariara, 2008, 2009; Rivera-Ferre and López-i-Gelats, 2012), who use many different strategies, including changing herd size and composition, grazing and feeding patterns, or diversifying their livelihoods; also they may use new varieties of fodder crops suited to the changing conditions (Salema et al., 2010).

Diversified farms are more resilient than specialized ones (Seo, 2010); but rural societies also diversify their income sources beyond agriculture, which in many contexts allows them to reduce their risk exposure. Examples include the exploitation of gums and resins in Kenya (Gachathi and Eriksen, 2011).There may be some rural areas, however, where limits to agricultural adaptation are reached, and thus the only option that remains is to migrate or diversify away from farming (Mertz et al., 2011). According to Chapter 7, adaptation leads to lower reductions in food production with more effective adaptation (of around 15 to 20% compared with no adaptation), and adaptations are more successful at higher latitudes (for maize, wheat, and rice) than in tropical regions. Figure 7-8 shows the varying efficiency of different crop adaptation measures, with cultivar adjustment leading to the largest percentage difference from the baseline, compared with irrigation optimization and planting date adjustment (although this shows the largest variation).

9.4.3.2. Water

As well as being an important input to agriculture, adaptation in water resources through improved management is critical in rural areas, not only at basin level but also for human settlements (Mukheibir, 2008). The extent to which adaptation measures have been implemented to date varies: in a study from Europe, Africa, and Asia, European basins were most advanced (Krysanova et al., 2010). In the cases of transboundary basins additional barriers exist to adaptive management measures, particularly in Africa (Goulden et al., 2009), although examination of potential institutional designs has been undertaken

Table 9-7 | Examples of adaptations in the agricultural sector in different regions.

Agricultural adaptations	Examples	Where observed	Source
Modifying planting, harvesting, and fertilizing practices for crops	Maize and wheat crops	Central and South America (Bolivia, Argentina, Chile); South Africa (including North West, Limpopo, and KwaZulu-Natal provinces)	PNCC (2007), Thomas et al. (2007), Magrin et al. (2009), Meza and Silva (2009)
	Composting and coralling of livestock to collect waste	Africa (South Africa, including North West, Limpopo, and KwaZulu-Natal provinces; northern Burkina Faso; Sahelian region of Mali)	Adepetu and Berthe (2007), Thomas et al. (2007), Barbier et al. (2009), Bryan et al. (2009)
Changing amount or area of land under cultivation		South Africa	Bryan et al. (2009)
	Moving winter wheat northwards	China	Lin et al. (2005)
	Expansion of fields	Northern Burkina Faso	Barbier et al. (2009)
	Increase in the size of plots	Sahelian region of Mali	Adepetu and Berthe (2007)
Using different varieties (e.g., early maturing, drought-resistant)	Early maturing cultivars	South Brazil	Walter et al. (2010)
		North America	Coles and Scott (2009)
	Drought-tolerant cultivars	Asia	Thomas (2008), Zhao et al. (2010)
		South Africa and Ethiopia	Bryan et al. (2009)
		Ghana	Gyampoh et al. (2008)
		Northern Burkina Faso	Barbier et al. (2009)
		Sahelian region of Mali and Nigeria	Adepetu and Berthe (2007)
		North West, Limpopo, and KwaZulu-Natal provinces of South Africa	Thomas et al. (2007)
Diversifying crops and/or animal species	Crops	Peruvian Andes	Lin (2011)
		South America	Montenegro and Ragrab (2010)
		Northeastern Mexico	Eakin and Appendini (2008), Eakin and Bojorquez-Tapia (2008)
		Tasmania, Australia	Smart (2010)
		KwaZulu-Natal, South Africa	Thomas et al. (2007)
	Replacing cattle with hardier goats and camels	Kenya	Rivera-Ferre and López-i-Gelats (2012)
Commercialization of agriculture		Ghana	Gyampoh et al. (2008)
		Limpopo Province, South Africa	Thomas et al. (2007)
	Income generation from natural resources (e.g., fuelwood)	Limpopo River Basin, Botswana	Dube and Sekhela (2007)
Water control mechanisms (including irrigation and water allocation rights)	Improved rice harvests	Monsoonal Asia	Hatcho et al. (2010)
	Adaptation for quinoa	Bolivian Altiplano	Geerts and Raes (2009)
	Adaptation for tomatoes	Central Brazil	
	Adaptation for cotton	Northern Argentina	
	Adaptation for rice	Northeast China	Lin et al. (2005)
	Small water harvesting pits in improved yields and incomes due to improved soil moisture	Ethiopia	Bryan et al. (2009), Amede et al. (2011)
		Burkina Faso	Barbier et al. (2009), Hertsgaard (2011)
		South Africa	Bryan et al. (2009)
		Ghana	Gyampoh et al. (2008)
	Dry season vegetable production through irrigation to enable two crop cycles	Northern Burkina Faso	Barbier et al. (2009)
		Sahelian region of Mali and Nigeria	Adepetu and Berthe (2007)
		Limpopo Province, South Africa	Thomas et al. (2007)
Shading and wind breaks	For coffee	Brazil, Costa Rica, and Colombia	Camargo (2010)
		Ethiopia	Bryan et al. (2009)
Conservation agriculture (e.g., soil protection, agroforestry)		Honduras, Nicaragua, and Guatemala	Holt-Gimenez (2002)
		Burkina Faso	Barbier et al. (2009), Hertsgaard (2011)
		Ethiopia	Bryan et al. (2009)
		Sahelian region of Mali	Adepetu and Berthe (2007)

Continued next page →

Table 9-7 (continued)

Agricultural adaptations	Examples	Where observed	Source
Modifying grazing patterns for herds	Utilizing spatial variability in resources	Arctic	Bartsch et al. (2010)
		East Africa	Eriksen and Lind (2009)
		Southern Africa	O'Farrell et al. (2009)
		Northern Burkina Faso	Barbier et al. (2009)
		Sahelian region of Mali and Nigeria	Adepetu and Berthe (2007)
		North West, Limpopo, and KwaZulu-Natal provinces, South Africa	Thomas et al. (2007)
Providing supplemental feeding for herds/storage of animal feed		Arctic	Forbes and Kumpula (2009)
		South Africa	Bryan et al. (2009)
	Use of sorghum and hay residue for feeding livestock	Northern Burkina Faso	Barbier et al. (2009)
		Sahelian region of Mali and Nigeria	Adepetu and Berthe (2007)
	Cutting fodder for livestock	Limpopo Province, South Africa	Thomas et al. (2007)
Ensuring optimal herd size	Changing size of European reindeer herds to match pasture availability	Northern areas of Norway, Sweden, Finland, and Russia	Rees et al. (2008)
	Culling of livestock	Northern Nigeria	Adepetu and Berthe (2007)
	Selling of livestock	Northern Burkina Faso	Barbier et al. (2009)
		Sahelian region of Mali and Nigeria	Adepetu and Berthe (2007)
Developing new crop and livestock varieties	Biotechnology and breeding	Brazil and Argentina	Urcola et al. (2010), Marshall (2012)
		Northern Nigeria	Adepetu and Berthe (2007)

(Huntjens et al., 2012). In the Middle East and North Africa, while supply-side measures are advanced, little attention has been paid to the demand-side measures that will be critical in a changing climate (Sowers et al., 2011).

While the majority of focus on adaptation concerning water relates to its availability, many rural areas in both developed and developing countries are subject to riverine or coastal flooding. In the low-lying Netherlands protection measures have been employed, including increasing river runoff, increasing storage for water (Deltacommissie, 2008; Kabat et al., 2009), and small-scale containment of flood risks through increasing compartmentalization (Klijn et al., 2009). In the Mekong Delta in Vietnam, the government's "living with floods" program has encouraged rice farmers to shift to aquaculture, while the planned relocation of 20,000 "landless and poor households" has altered social networks and livelihoods (De Sherbinin et al., 2011). See Table 9-8 for further examples.

More information on adaptation in the water sector is available in Sections 24.4.1.5 and 24.4.2.5 (Asia), 26.3.3 (North America), and 27.3.1.2 and 27.3.2.2 (Central and South America).

9.4.3.3. Forestry and Biodiversity

Effective management is also essential for adaptation of forests and biodiversity to climate change, particularly involving (where appropriate) communities (Porter-Bolland et al., 2012). Forest resources have been shown to play a role in enabling livelihood adaptation during extreme events in Zambia, Mali, and Tanzania, although it should take place

Table 9-8 | Examples of adaptations in the water sector observed in different regions.

Type	Example	Where it has been observed and source
Supply-side mechanisms	Dams	Proposed in the Volta River in Ghana (van de Giesen et al., 2010)
	Reservoirs	Asia (Tyler and Fajber, 2009), particularly in areas where water stress is an issue of distribution rather than absolute shortage (Biemans et al., 2011; Rivera-Ferre et al. 2013)
	Groundwater pumping	Arid and semi-arid South America (Döll, 2009; Kundzewicz and Döll, 2009; Zagonari, 2010; Burte et al., 2011)
	Groundwater recharge	Potential identified in India (Sukhija, 2008)
	Irrigation (often using water-saving technology)	Asia (Ngoundo et al., 2007; Tischbein et al., 2011)
	Fog interception practices	South America (Holder, 2006; Klemm et al., 2012)
	Water capture	Bolivia (PNCC, 2007)
Demand-side mechanisms	Improved management, e.g., through efficiency	Asia (Kranz et al., 2010), South America (Geerts et al., 2010; Montenegro and Ragab, 2010; Van Oel et al., 2010; Bell et al., 2011); Argentine Pampas (Quiroga and Gaggioli, 2010)
	Policies	Murray-Darling Basin Authority (MDBA) established to address over-allocation of water resources (Connell and Grafton, 2011; MDBA, 2011). See also Box 25-3 on Australia's water policies.
	Reviewing allocation rights	Indogangetic Plains (Rivera-Ferre et al., 2013b); Australia's MDBA reviewed the "exceptional circumstances" concept in drought policy (Productivity Commission, 2009)

Box 9-3 | Adaptation Initiatives in the Beverage Crop Sector

One of the leading initiatives to prepare small-holder producers of beverage crops for adaptation to climate change is the AdapCC project, which worked with coffee and tea producers in Latin America and East Africa (Schepp, 2010). This process used risk and opportunity analysis and participatory capacity building (CafeDirect/GTZ, 2010) to help farmers identify changes in management practices to both mitigate their contribution to climate change and adapt to the changes in climate they perceived to be occurring. In general the actions for adaptation were a reinforcement of principles of sustainable production, such as using tree shade. Facilitating processes of adaptation in the context of strong variability in vulnerability between different communities in the same region and even families within the same community (Baca Gómez, 2010) will be a challenge, but supports the need for participatory community adaptation processes that would enable families to implement strategies appropriate to their own circumstances and capacity.

Policy recommendations to support adaptation in these sectors (Schroth et al., 2009; Laderach et al., 2010; Schepp, 2010; Eakin et al., 2011) have prioritized the following interventions to support adaptation:

- Community-based analysis of climate risks and opportunities as a basis for community adaptation strategies
- Improved recording and access to climate information including medium- and long-term predictions
- Sustainable production techniques including soil and water conservation, shaded production systems, diversification of production systems
- Development of new varieties with broader adaptability to climate variation, higher temperatures, and increased drought tolerance
- Financial support to invest in adaptation and reduce risks through climate insurance
- Organization of small producers to improve access to knowledge and financial support, and to coordinate implementation
- Environmental service payments and access to carbon markets to support sustainable practices
- Development of value chain strategies across all actors to support adaptation and increase resilience across the sectors.

There are possibilities for synergy between adaptation and mitigation. The sustainability standards Rainforest Alliance and Common Code for the Coffee Community are piloting climate-friendly standards for producers that aim to reduce the greenhouse gas emissions from agricultural practices and to increase sequestration of carbon in soils and trees, but also to prepare producers for adapting to climate change (Linne, 2011; SAN, 2011). The latter consists of improved understanding of climate impacts and promoting sustainable production practices to increase resilience in the production systems.

within a managed context to ensure sustainability (Robledo et al., 2011). As with water resources, forests can adapt through management of forest fires, silvicultural practices, and the conservation of forest genetic resources. Ecological restoration, where required, is another effective adaptation measure that enhances biodiversity and environmental services (Benayas et al., 2009), increases the potential for carbon sequestration, and promotes economic livelihoods in rural areas (Chazdon, 2008), as seen in examples of the Brazilian Atlantic Forest (Calmon et al., 2011; Rodrigues et al., 2011). Direct species management is important (Mawdsley et al., 2009). In terms of managing protected areas, to maintain appropriate habitats a network approach may be effective (Hole et al., 2011).

As the climate changes, part of adaptive management may entail modification of existing biodiversity management practices. Manipulating vegetation composition and stand structure, for example, has been proposed as an adaptation option to wildfires in Canada (Girardin et al., 2013; Terrier et al., 2013); for more information on wildfires see Box 26-2. In Central and South America, protected areas of restricted use reduced fire substantially, but multi-use protected areas are even more effective; and in indigenous reserves the incidence of forest fire was reduced by 16% as compared to non-protected areas (Nelson and Chomitz, 2011).

Reflecting the growing evidence for community-based management and wise use, an emerging mechanism for ecosystem-based adaptation includes payment for ecosystem services (PES) (Montagnini and Finney, 2011). The PES literature is more developed for carbon payments, CDM and REDD+, but some research suggests potential for adaptation as well (see Section 13.3.1.2 for an assessment of the relationship between REDD+ and poverty alleviation). Particularly developed in Central and South America (see Table 27-7 for examples of PES schemes), communities can be paid for collecting scientific data to contribute to research and monitoring protocols (Luzar et al., 2011), or for actively managing natural resources, which may improve adaptive capacity in the longer term, bearing in mind with reforestation there is a time delay before payments are received (Locatelli et al., 2008). More indirectly, there are opportunities for PES to contribute to adaptation indirectly through

natural adaptation co-benefits (e.g., water regulation and soil protection for reduced climate impacts in watersheds) (Pramova et al., 2012) and through the creation of institutional structures that may support adaptive capacity (Wertz-Kanounnikof et al., 2012). For further case studies on ecosystem-based adaptation, see Figure 22-8 (Africa), Box CC-EA, and Section 14.3.2; and for a diagrammatic representation see Figure CC-EA-1. More information on adaptation for forestry and biodiversity is available in Sections 23.8.2 and 23.8.4 (Europe), 24.5.1 (Asia), and 25.7.1.2 (Australasia).

9.4.3.4. Fisheries

Adaptation in marine ecosystems is also of relevance to rural areas. As with terrestrial natural resources, evidence from the marine resources sphere shows that a transformative approach to fisheries co-management, introducing ecosystem rights, and participation principles is essential for adaptation (Andrew and Evans, 2011; Charles, 2011). Such an approach, involving local fishermen and allowing limited extraction of resources, favors a balance between resource conservation and livelihoods, for example, in Brazil (Francini-Filho and Moura, 2008), and the improvement of livelihoods, as well as the cultural survival of traditional populations (Moura et al., 2009; Hastings, 2011) (see also Section 30.6.2.1). Selective use of fishing gear is a recommended management measure, based on 15 global sites, to ensure sustainable harvesting of remaining fish stocks (Cinner et al., 2009). According to Section 6.4.1.1, appropriate management will have a greater impact on biological and economic conditions than climate change. Table 30-2 outlines potential adaptation options and supporting policies for fisheries and aquaculture in the Pacific Islands considering a variety of time scales. Section 7.5 gives additional examples on adaptation for aquaculture.

9.4.4. Limits and Constraints to Rural Adaptation

The Fourth Assessment Report stated with *very high confidence* that there are substantial limits and barriers to adaptation (Adger et al., 2007). Limits are typically defined (Dow et al., 2013) as hard, that is, they will not change over time, and are particularly applicable to biophysical systems (where, e.g., there are critical thresholds to species and ecosystem tolerances of climate parameters and regimes). Constraints, on the other hand, are typically soft, and are more relevant to social systems, where changes in factors such as financial and physical resources, technology and infrastructure, knowledge and information, and human resources may change over time. For further information, see Figure 16-1 and Sections 16.3.2 and 16.4.1. Here we focus on the soft constraints in social systems that act as barriers to implementation of practical adaptation options in rural areas.

As with risks and vulnerabilities, the literature emphasizes constraints to adaptation in rural areas in developing regions, although adaptation bottlenecks exist also in developed countries (where there has been an increase in awareness and planning for adaptation, but that has not necessarily translated into implementation; see Chapter 14). Constraints to adaptation in developed regions have been observed in North America (Section 26.8.4.2) and Australasia (Section 25.4.2; Boxes 25-1, 25-2, 25-9). Another key bottleneck comes from the fact that the need for adaptation to climate change is not the only pressing issue in rural areas in developed countries (Kiem and Austin, 2013).

There is *very high confidence* that lack of financial resources (in the form of credit) and physical resources (such as water and land) are major factors inhibiting adaptation for farmers in Africa and Asia (e.g., Hassan and Nhemachena, 2008; Bryan et al., 2009; Deressa et al., 2009; Ringler, 2010). A multinomial logit analysis of climate adaptation responses suggested that access to water, credit, extension services, and off-farm income and employment opportunities, tenure security, farmers' asset base, and farming experience are key to enhancing farmers' adaptive capacity (Gbetibouo et al., 2010).

Rural households' lack of access to technologies and infrastructure (e.g., markets) is also a major barrier to adaptation for certain production systems (*medium evidence*, *high agreement*). According to a study of adoption of improved, high yield maize in Zambia, production and price risks could render input use unprofitable and prevent rural households from benefiting from technological change crucial for adaptation (Langyintuo and Mungoma, 2008). The severe 1997 drought in the Central Plateau of Burkina Faso highlighted that households with a larger resources base took advantage of distress sales and high prices of agricultural commodities (Roncoli et al., 2001). A nationally representative rural household survey in Mozambique from 2005 shows that, overall, using an improved technology (improved maize seeds, improved granaries, tractor mechanization, and animal traction) did not have a

Frequently Asked Questions

FAQ 9.3 | What will be the major ways in which rural people adapt to climate change?

Rural people will in some cases adapt to climate change using their own knowledge, resources, and networks. In other cases governments and other outside actors will have to assist rural people, or plan and execute adaptation on a scale that individual rural households and communities cannot. Examples of rural adaptations will include modifying farming and fishing practices; introducing new species, varieties, and production techniques; managing water in different ways; diversifying livelihoods; modifying infrastructure; and using or establishing risk-sharing mechanisms, both formal and informal. Adaptation will also include changes in institutional and governance structures for rural areas.

Box 9-4 | Factors Influencing Uptake and Utility of Climate Forecasts in Rural Africa

The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) identified the use of forecasts as a risk management measure (IPCC, 2012). So far the uptake of weather and climate information has been suboptimal (Vogel and O'Brien, 2006). In Africa annual climate information (e.g., seasonal forecasts) is more used than climate change scenarios for agricultural development (Ziervogel and Zermoglio, 2009), although attempts to use longer-term climate projections for crop forecasting and livestock farming have been examined (Boone et al., 2004; Challinor, 2009). The potential for improved prediction and effective timely dissemination of such information has been noted in different sectors, including water managers (Ziervogel et al., 2010a) and disaster planners (Tall et al., 2012), as well as farmers (both arable and pastoral) (Klopper et al., 2006; Archer et al., 2007; Bryan et al., 2009).

Extensive research has taken place to assess factors influencing uptake and utility of climate forecasts, including mapping of dissemination through stakeholder networks (Ziervogel and Downing, 2004), and user needs (Ziervogel, 2004). Such studies have shown that various factors affect dissemination and use, including stakeholder involvement in the process (usually higher when participatory processes had taken place) (Roncoli et al., 2009; Peterson et al., 2010); effects of user wealth, risk aversion, and presentational parameters, such as the position of forecast parameter categories, and the size of probability categories (Millner and Washington, 2011); and the legitimacy, salience, access, understanding, and capacity to respond (Hansen et al., 2011). Gender differences have been observed in preferred dissemination channels (Archer, 2003; Naab and Korenteng, 2012).

There are promising signs for the integration of scientific-based seasonal forecasts with indigenous knowledge systems (Speranza et al., 2010; Ziervogel et al., 2010b). Ensuring improved validity and utility of seasonal forecasts will require collaboration of researchers, data providers, policy developers, and extension workers (Coe and Stern, 2011), as well as with end users. Additional opportunities to benefit rural communities come from expanding the use of seasonal forecast information for coordinating input and credit supply, food crisis management, trade, and agricultural insurance (Hansen et al., 2011). For more information on climate information and services, and the history, politics, and practice of this area, see Section 2.4.1.

statistically significant impact on household income. However when distinguishing between households using improved technologies, especially improved maize seeds and tractors, and those who do not, households that had better market access had significantly higher income (Cunguara and Darnhofer, 2011). A multinomial choice model fitted to data from a cross-sectional survey of more than 8000 farms from 11 African countries showed that better access to markets, extension and credit services, technology, and farm assets (labor, land, and capital) are critical for helping African farmers adapt to climate change. Hence education, markets, credit, and information about adaptation to climate change, including technological and institutional methods, are important (Hassan and Nhemachena, 2008).

Although access to credit, water, technologies, and markets are barriers, more fundamental is access to knowledge and information (*very high confidence*). Because adaptation strategies involve dealing with uncertainty, whether stakeholders have access to information for decision making and how they perceive and utilize this information affects their adaptation choices (Dockerty et al., 2006; Sheate et al., 2008; Patt and Schröter, 2008; Bryan et al., 2009; Deressa et al., 2009; Ringer, 2010). Relevant information includes that on agricultural technologies that can be used in adaptation, but in developing countries agricultural research and extension systems are not integrated with climate planning to deliver this, as discussed by Moumouni and Idrissou (2013a) for Benin. There is now an important literature on dissemination of short-term or seasonal weather forecasts to farmers in developing countries (see Box 9-4).

Access to information is affected by human resources, or social characteristics (*medium evidence*, *high agreement*). These include culture, gender, age, governance, and institutions (Deressa et al., 2009; Goulden et al., 2009; Nielsen and Reenberg, 2010; Jones and Boyd, 2011). A growing body of literature investigates the socio-cognitive, psychological, and cultural barriers to adaptation. Section 2.2.1.2 explains how culture and psychology affect decision making; Section 16.2 also discusses how the framing of adaptation depends on perception of risk and values. For planned adaptation to be successful, or autonomous adaptation to occur, actors need to be convinced of the magnitude of risks of climate change (Patt and Schröter, 2008).

9.5. Key Conclusions and Research Gaps

9.5.1. Key Conclusions

This chapter has assessed impacts of climate change, vulnerability to climate change, and prospects for adaptation to climate change in the

rural areas of the world. Rural areas are distinctive and important in the context of climate change because:

- They account for nearly half of the world's population, even with rapid urbanization.
- They account for well over half of the world's poor and extremely poor people.
- Economic activity and livelihoods in rural areas are closely linked to natural resources and thus particularly sensitive to climate variability and climate change.
- Conversely, it is in rural areas that long-established adaptations to climate variability exist and can form a basis under certain conditions for adaptations to climate change.

Rural areas are hard to define—there is no internationally valid definition, and definitions that do exist depend on definitions of the urban (see Table 9-1). They are also extremely diverse, existing in nearly every country of the world, across low-, middle-, and high-income countries, although 90% of the world's rural population lives in low- and middle-income countries, which receive particular attention in this chapter. Rural areas are undergoing important and rapid changes in terms of their demography, economic profile, and governance (see Table 9-3)—some specific to developing countries, some to high-income countries, and some generic. Many of these changes are in the direction of economic and livelihood diversification away from agriculture and natural resources. Others are in the direction of increased rural-urban interdependencies and less well-defined boundaries between the rural and the urban.

Many of the non-climate factors characterizing rural areas and populations within them, especially in low- and middle-income countries, are cited as factors increasing vulnerability to climate change. There is *high agreement* on the importance for resilience of access to land and natural resources, flexible local institutions, and knowledge and information, and the association of gender inequalities with vulnerability. There are *low levels of agreement* on some of the key factors associated with vulnerability or resilience in rural areas, including rainfed as opposed to irrigated agriculture, small-scale and family-managed farms, and integration into world markets. Specific livelihood niches such as pastoralism and artisanal fisheries are vulnerable and at high risk of adverse impacts (*high confidence*), partly due to neglect, misunderstanding, or inappropriate policy toward them on the part of governments (Section 9.3.5).

Against this background, discussion of impacts of climate change will be complex. The impacts of climate change on patterns of settlement, livelihoods, and incomes in rural areas will be the result of multi-step causal chains of impact, starting either with increased frequency of extreme events or with more gradual manifestations of climate change, and working through impacts on agriculture, ecosystems, or infrastructure. This increases the uncertainty associated with any particular projected impact. Biophysical impacts on food production are discussed in Chapter 7: this is supplemented here by an assessment of impacts on the production of non-food crops on which many millions of rural people depend, illustrated in particular by coffee, tea, and cocoa (Box 9-1). Literature on the downstream impacts on incomes and livelihoods of changes in agricultural production (including livestock and fisheries) is also assessed.

Despite methodological problems in attribution, around the difficulties of attributing extreme events to climate change, the status of local knowledge, and the action of non-climate shocks and trends, evidence for observed impacts, both of extreme events and other categories, is increasing. Impacts on income and livelihoods can be inferred from biophysical impacts, but with *low confidence*. There is *high confidence* in geographically specific impacts such as glacier melt in the Andes (Section 9.3.2).

Major impacts of climate change in rural areas will be felt through impacts on agricultural production and therefore through agricultural incomes. In some regions shifts in agricultural production, of food and non-food crops, are *likely* to take place, not only as a result of changes in temperature and rainfall, but also through changes in availability of irrigation water, which are not necessarily factored into crop yield projections based on crop models (Section 9.3.3.1). There are also *likely* to be impacts on rural infrastructure both in developing and developed countries (Section 9.3.3.2).

The interconnections between rural and urban areas will be affected in complex ways. Climate change will impact international trade volumes in both volume and value terms (*limited evidence*, *medium agreement*). Options exist for adaptations within international agricultural trade (*medium confidence*) to reduce market volatility and manage food supply shortages caused by climate change. Migration patterns will be driven by multiple factors of which climate change is only one (*high confidence*) and establishment of a relation between climate change and intra-rural and rural-to-urban migration, observed or projected, remains a major challenge (Section 9.3.3.3).

Climate policies, such as increasing energy supply from renewable resources, encouraging cultivation of biofuels, or payments under REDD, will have significant secondary impacts, both positive (increasing employment opportunities) and negative (landscape changes, increasing conflicts for scarce resources), in some rural areas (*medium confidence*). These secondary impacts, and trade-offs between mitigation and adaptation in rural areas, have implications for governance, including the need to promote participation of rural stakeholders (Section 9.3.3.4).

Most studies on valuation highlight that climate change impacts will be significant especially for the developing regions, due to their economic dependence on agriculture and natural resources, low adaptive capacities, and geographical locations (*very high confidence*). In rural areas especially, valuation of climate impacts needs to draw upon both monetary and non-monetary indicators.The valuation of non-marketed ecosystem services and the limitations of economic valuation models that aggregate across multiple contexts pose challenges for valuing impacts in rural areas and require interdisciplinarity and innovative approaches (Section 9.3.4).

There is a growing body of literature on successful adaptation in rural areas and constraints upon it, including both documentation of practical experience and discussion of preconditions (Section 9.3.4). In developing countries adaptation can be linked to other development initiatives aiming for poverty reduction or improvement of rural areas, and "low regrets" measures to respond to current variability can shift the trajectory from disaster-focused to longer-term vulnerability reduction. Prevailing

constraints, such as low levels of educational attainment, environmental degradation, gender inequalities, and isolation from decision making, create additional vulnerabilities which undermine rural societies' ability to cope with climate risks (*high confidence*). The supply of information and opportunities for learning will be a key issue.

9.5.2. Research Gaps

There is a major continuing need for research on climate change in rural areas, which takes in their nature as areas with shifting combinations of human activity, in which agriculture (food crops, non-food crops, and livestock) is important but not necessarily predominant. Such research will need to be developed, and extended to rural areas and diverse categories of rural people throughout the world.

Integrated research is needed on changes in land use and trade-offs between land uses under climate change, including non-agricultural land uses such as conservation and tourism. It should examine the trade-offs and synergies between adaptation and mitigation in rural areas, the impact of climate policies on rural livelihoods, and the appropriate structures for governance of natural resources at a landscape level for both developed and developing countries.

Research is required on the valuation and costing of climate change impacts, which takes note of the complexity and specificity of rural areas, with special emphasis on non-marketed ecosystem services and specific populations that have not as yet been studied.

More research is needed on vulnerability, to identify the most vulnerable areas, populations, and social categories, but it should include research on methodological questions such as conceptualizations of vulnerability, assessment tools, spatial scales for analysis, and the relations between short-term support for adaptation, policy contexts and development trajectories, and long-term resilience or vulnerability.

A relevant area will be that of improving understanding of rural-urban linkages, their evolution, and their management under climate change, including the respective roles of climate and other factors in rural-urban migration.

Research is needed on practical adaptation options, not only for agriculture but also for non-agricultural livelihoods. Adaptation research must also look at adaptations to institutions, to better enable them to address lack of access to credit, markets, information, risk-sharing tools, and property rights. Research must be open to participatory and action-research approaches that build on both local and scientific knowledge, and foster learning for adaptation and resilience among rural people.

References

Abbott, P.C., C. Hurt, and W.E. Tyner, 2008: *What's Driving Food Prices?* Farm Foundation Issue Report, Farm Foundation, Oak Brook, IL, USA, 80 pp.

Ackerman, F., S.J. DeCanio, R.B. Howarth, and K. Sheeran, 2009: Limitations of integrated assessment models of climate change. *Climatic Change*, **95(3-4)**, 297-315.

ADB, 2009: *Understanding and Responding to Climate Change in Developing Asia.* Asian Development Bank (ADB), Mandaluyong City, Metro Manila, Philippines, 74 pp.

ADB, 2012: *Addressing Climate Change and Migration in Asia and the Pacific.* Asian Development Bank (ADB), Mandaluyong City, Metro Manila, Philippines, 82 pp.

ADB and IFPRI, 2009: *Building Climate Resilience in the Agriculture Sector in Asia and the Pacific.* Asian Development Bank (ADB) and International Food Policy Research Institute (IFPRI), Mandaluyong City, Metro Manila, Philippines, 304 pp.

Adepetu, A. and A. Berthe, 2007: *Vulnerability of Rural Sahelian Households to Drought: Options for Adaptation.* Final Report Submitted to Assessments of Impacts and Adaptations to Climate Change (AIACC), Project No. AF 92, AIACC Project Office, The International START Secretariat, Washington, DC, USA, 72 pp.

Adger, W.N., S. Agrawala, M.M.Q. Mirza, C. Conde, K. O'Brien, J. Pulhin, R. Pulwarty, B. Smit and K. Takahashi, 2007: Assessment of adaptation practices, options, constraints and capacity. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 717-743.

Adger, W.N., J. Barnett, F.S. Chapin III, and H. Ellemor, 2011: This must be the place: underrepresentation of identity and meaning in climate change decision-making. *Global Environmental Politics*, **11(2)**, 1-25.

Adhikari, B. and K. Taylor, 2012: Vulnerability and adaptation to climate change: a review of local actions and national policy response. *Climate and Development*, **4(1)**, 54-65.

Afifi, T., 2011: Economic or environmental migration? The push factors in Niger. *International Migration*, **49(Suppl. 1)**, e95-e124.

Agrawal, A. and N. Perrin, 2009: Climate adaptation, local institutions and rural livelihoods. In: *Adapting to Climate Change* [Adger, W.N., I. Lorenzoni, and K.L. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK, pp. 350-367.

Ahmed, S.A., N.S. Diffenbaugh, and T.W. Hertel, 2009: Climate volatility deepens poverty vulnerability in developing countries. *Environmental Research Letters*, **4(3)**, 034004, doi:10.1088/1748-9326/4/3/034004.

Ahmed, S.A., N.S. Diffenbaugh, T.W. Hertel, D.B. Lobell, N. Ramankutty, A.R. Rios, and P. Rowhani, 2011: Climate volatility and poverty vulnerability in Tanzania. *Global Environmental Change*, **21(1)**, 46-55.

Ahmed, S.A., N.S. Diffenbaugh, T.W. Hertel, and W.J. Martin, 2012: Agriculture and trade opportunities for Tanzania: past volatility and future climate change. *Review of Development Economics*, **16(3)**, 429-447.

Ainsworth, C.H. and U.R. Sumaila, 2005: Intergenerational valuation of fisheries resources can justify long-term conservation: a case study in Atlantic cod (*Gadus morhua*). *Canadian Journal of Fisheries and Aquatic Sciences*, **62(5)**, 1104-1110.

Alderman, H., 2010: Safety nets can help address the risks to nutrition from increasing climate variability. *The Journal of Nutrition*, **140(Suppl. 1)**, 148S-152S.

Allison, E.H., A.L. Perry, M. Badjeck, W. Neil Adger, K. Brown, D. Conway, A.S. Halls, G.M. Pilling, J.D. Reynolds, N.L. Andrew, and N.K. Dulvy, 2009: Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries*, **10(2)**, 173-196.

Aldred J., 2012: Climate change uncertainty, irreversibility and the precautionary principle. *Cambridge Journal of Economics*, **36(5)**, 1051-1072.

Alston, M., 2011: Gender and climate change in Australia. *Journal of Sociology*, **47(1)**, 53-70.

Amede, T., M. Menza, and S.B. Awlachew, 2011: Zai improves nutrient and water productivity in the Ethiopian highlands. *Experimental Agriculture*, **47(Suppl. S1)**, 7-20.

Anderson, S., J. Morton, and C. Toulmin, 2010: Climate change for agrarian societies in drylands: implications and future pathways. In: *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World* [Mearns, R. and A. Norton (ed.)]. World Bank, Washington, DC, USA, pp. 199-230.

Anderson, K. and S. Nelgen, 2012: Trade barrier volatility and agricultural price stabilization. *World Development*, **40(1)**, 36-48.

Andrew, N.L. and L. Evans, 2011: Approaches and frameworks for management and research in small-scale fisheries. In: *Small-Scale Fisheries Management: Frameworks and Approaches for the Developing World* [Pomeroy, R.S. and N. Andrew (eds.)]. CABI, Wallingford, UK and Cambridge, MA, pp. 16-34.

Anseeuw, W., M. Boche, T. Breu, M. Giger, J. Lay, P. Messerli, and K. Nolte, 2012: *Transnational Land Deals for Agriculture in the Global South.* Analytical Report based on the Land Matrix Database, The Centre for Development and Environment

(CDE), Bern, Switzerland, CIRAD, Montpellier, France, and the German Institute of Global and Area Studies (GIGA), Hamburg, Germany, The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Bonn, Germany, 50 pp.

Archer, E. 2003: Identifying underserved end-user groups in the provision of climate information. *Bulletin of the American Meteorological Society*, **84(11)**, 1525-1532.

Archer, E., E. Mukhala, S. Walker, M. Dilley, and K. Masamvu, 2007: Sustaining agricultural production and food security in Southern Africa: an improved role for climate prediction? *Climatic Change*, **83**, 287-300.

Assad, E.D., H.S. Pinto, J.Z. Junior, and A.M.H. Avila, 2004: Climatic changes impact in agroclimatic zonning of coffee in Brazil. *Pesquisa Agropecuaria Brasileira*, **39(11)**, 1057-1064.

Asseng, S., M.I. Travasso, F. Ludwig, and G.O. Magrin, 2013: Has climate change opened new opportunities for wheat cropping in Argentina? *Climatic Change*, **117(1-2)**, 181-196.

Australian Bureau of Statistics, 2013: *Frequently Asked Questions*. Commonwealth of Australia, Australian Bureau of Statistics, Belconnen, ACT, Australia, www.abs.gov.au/websitedbs/D3310114.nsf/home/Frequently+Asked+Questions#Anchor7.

Baca Gómez, M.G., 2010: *Identificación de la Vulnerabilidad en los Medios de Vida de las Familias Cafetaleras y sus posibles Estrategias de Adaptación al Cambio Climático en el norte de Nicaragua*. MSc thesis, CATIE, Turrialba, Costa Rica, 166 pp.

Backus, G.A., T.S. Lowry, and D.E. Warren, 2013: The near-term risk of climate uncertainty among the U.S. states. *Climatic Change*, **116(3-4)**, 495-522.

Badjeck, M., E.H. Allison, A.S. Halls, and N.K. Dulvy, 2010: Impacts of climate variability and change on fishery-based livelihoods. *Marine Policy*, **34(3)**, 375-383.

Barbier, B., H. Yacouba, H. Karambiri, M. Zorome, and B. Some, 2009: Human vulnerability to climate variability in the Sahel: farmers' adaptation strategies in northern Burkina Faso. *Environmental Management*, **43**, 790-803.

Barrett, C.B. and D.G. Maxwell, 2006: Towards a global food aid compact. *Food Policy*, **31(2)**, 105-118.

Bartsch, A., T. Kumpula, B.C. Forbes, and F. Stammler, 2010: Detection of snow surface thawing and refreezing in the Eurasian Arctic with QuikSCAT: implications for reindeer herding. *Ecological Applications*, **20(8)**, 2346-2358.

Beaumier, M.C. and J.D. Ford, 2010: Food insecurity among Inuit women exacerbated by socioeconomic stresses and climate change. *Canadian Journal of Public Health*, **101(3)**, 196-201.

Bell, A.R., N.L. Engle, and M.C. Lemos, 2011: How does diversity matter? The case of Brazilian river basin councils. *Ecology and Society*, **16(1)**, 42.

Bellon, M.R., D. Hodson, and J. Hellin, 2011: Assessing the vulnerability of traditional maize seed systems in Mexico to climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **108(33)**, 13432-13437.

Benayas, J.M.R., A.C. Newton, A. Diaz, and J.M. Bullock, 2009: Enhancement of biodiversity and ecosystem services by ecological restoration: a meta-analysis. *Science*, **325(5944)**, 1121-1124.

Beniston, M., 2010: Impacts of climatic change on water and associated economic activities in the Swiss Alps. *Journal of Hydrology*, **412**, 291-296.

Berrang-Ford, L., J.D. Ford, and J. Paterson, 2011: Are we adapting to climate change? *Global Environmental Change: Human and Policy Dimensions*, **21(1)**, 25-33.

Biemans, H., I. Haddeland, P. Kabat, F. Ludwig, R.W.A. Hutjes, J. Heinke, W. von Bloh, and D. Gerten, 2011: Impact of reservoirs on river discharge and irrigation water supply during the 20th century. *Water Resources Research*, **47(3)**, W03509, doi:10.1029/2009WR008929.

Bigano, A., J.M. Hamilton, and R.S.J. Tol, 2007: The impact of climate change on domestic and international tourism: a simulation study. *The Integrated Assessment Journal*, **7(1)**, 25-49.

Black, R., D. Kniveton, and K. Schmidt-Verkerk, 2011: Migration and climate change: towards an integrated assessment of sensitivity. *Environment and Planning*, **43(2)**, 431-450.

Black, R., W.N. Adger, N.W. Arnell, S. Dercon, A. Geddes, and D. Thomas, 2011: The effect of environmental change on human migration. *Global Environmental Change*, **21(Suppl. 1)**, S3-S11.

Blair, A., D. Kay, and R. Howe, 2011: *Transitioning to Renewable Energy: Development Opportunities and Concerns for Rural America.* RUPRI Rural Futures Lab Foundation Paper No. 2, Community and Regional Development Institute (CaRDI), Cornell University, Ithaca, NY, USA, 60 pp.

Boko, M., I. Niang, A. Nyong, C. Vogel, A. Githeko, M. Medany, B. Osman-Elasha, R. Tabo, and P. Yanda, 2007: Africa. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., J.P. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 433-467.

Boone, R.B., K.A. Galvin, M.B. Coughenour, J.W. Hudson, P.J. Weisberg, C.H. Vogel, and J.E. Ellis, 2004: Ecosystem modelling adds value to a South African climate forecast. *Climatic Change*, **64**, 317-340.

Bowyer-Bower, T., 2006: The inevitable illusiveness of 'sustainability' in the peri-urban interface: the case of Harare. In: *The Peri-Urban Interface: Approaches to Sustainable Natural and Human Resource Use* [McGregor, D., D. Simon, and D. Thompson (eds.)]. Earthscan, London, UK and Sterling, VA, USA, pp. 150-164.

Boyd, R. and M.E. Ibarraran, 2009: Extreme climate events and adaptation: an exploratory analysis of drought in Mexico. *Environment and Development Economics*, **14(3)**, 371-395.

Brekke, K.A. and O. Johansson-Stenman, 2008: The behavioural economics of climate change. *Oxford Review of Economic Policy*, **24(2)**, 280-297.

Brondizio, E.S. and E.F. Moran, 2008: Human dimensions of climate change: the vulnerability of small farmers in the Amazon. *Philosophical Transactions of the Royal Society B*, **363(1498)**, 1803-1809.

Brouder, P. and L. Lundmark, 2011: Climate change in Northern Sweden: intra-regional perceptions of vulnerability among winter-oriented tourism businesses. *Journal of Sustainable Tourism*, **19(8)**, 919-933.

Brouwer, R., S. Akter, L. Brander, and E. Haque, 2007: Socioeconomic vulnerability and adaptation to environmental risk: a case study of climate change and flooding in Bangladesh. *Risk Analysis*, **27(2)**, 313-326.

Brown, D.G., D.T. Robinson, M. Zellner, W. Rand, R. Riolo, S.E. Page, J.I. Nassauer, B. Low, Z. Wang, and L. An, 2008: Exurbia from the bottom-up: confronting empirical challenges to characterizing a complex system. *Geoforum*, **39(2)**, 805-818.

Brown, D., F. Seymour, and L. Peskett, 2008: How do we achieve REDD co-benefits and avoid doing harm? In: *Moving Ahead with REDD: Issues, Options and Implications* [Angelsen, A. (ed.)]. Center for International Forestry Research (CIFOR), Bogor, Indonesia, pp. 107-118.

Brown, O., 2008: *Migration and Climate Change.* IOM Migration Research Series No 31, International Organization for Migration (IOM), IOM, Geneva, Switzerland, 54 pp.

Brown, O. and A. Crawford, 2008: Climate change: a new threat to stability in West Africa? Evidence from Ghana and Burkina Faso. *African Security Review*, **17(3)**, 39-57.

Brugger, J. and M.A. Crimmins, 2012: *Weather, Climate, and Rural Arizona: Insights and Assessment Strategies.* A Technical Input to the U.S. National Climate Assessment, University of Arizona, Tucson, AZ, USA, 80 pp.

Bryan, E., T.T. Deressa, G.A. Gbetibouo, and C. Ringler, 2009: Adaptation to climate change in Ethiopia and South Africa: options and constraints. *Environmental Science and Policy*, **12**, 413-426.

Bunce, M., 2008: The 'leisuring' of rural landscapes in Barbados: new spatialities and the implications for sustainability in small island states. *Geoforum*, **39(2)**, 969-979.

Burte, J.D.P., A. Coudrain, and S. Marlet, 2011: Use of water from small alluvial aquifers for irrigation in semi-arid regions. *Revista Ciência Agronômica*, **42(3)**, 635-643.

Bury, J.T., B.G. Mark, J.M. McKenzie, A. French, M. Baraer, K.I. Huh, M.A. Zapata Luyo, and R.J. Gómez López, 2011: Glacier recession and human vulnerability in the Yanamarey watershed of the Cordillera Blanca, Peru. *Climatic Change*, **105(1)**, 179-206.

Cafédirect and GTZ, 2011: *Climate Change and Coffee: Training for Coffee Organizations and Extension Services.* Cafédirect and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, GTZ, Eschborn, Germany, 76 pp.

Calmon, M., P.H.S. Brancalion, A. Paese, J. Aronson, P. Castro, S.C. de Silva, and R.R. Rodrigues, 2011: Emerging threats and opportunities for large-scale ecological restoration in the Atlantic forest of Brazil. *Restoration Ecology*, **19(2)**, 154-158.

Camargo, M.B.P., 2010: The impact of climatic variability and climate change on arabic coffee crop in Brazil. *Bragantia*, **69(1)**, 239-247.

Campbell, B.M., 2009: Beyond Copenhagen: REDD+, agriculture, adaptation strategies and poverty. *Global Environmental Change*, **19(4)**, 397-399.

Carey, M., 2010: *In the Shadow of Melting Glaciers: Climate Change and Andean Society.* Oxford University Press, New York, NY, USA, 288 pp.

Carey, M., C. Huggel, J. Bury, C. Portocarrero, and W. Haeberli, 2012: An integrated socio-environmental framework for glacier hazard management and climate change adaptation: lessons from Lake 513, Cordillera Blanca, Peru. *Climatic Change*, **112(3-4)**, 733-767.

Casale, M., S. Drimie, T. Quinlan, and G. Ziervogel, 2010: Understanding vulnerability in southern Africa: comparative findings using a multiple-stressor approach in South Africa and Malawi. *Regional Environmental Change*, **10(2)**, 157-168.

Castro, A.P., D. Taylor, and D.W. Brokensha, 2012: *Climate Change and Threatened Communities: Vulnerability, Capacity, and Action.* Practical Action Publishing, Bourton-on-Dunsmore, UK, 224 pp.

Challinor, A., 2009: Towards the development of adaptation options using climate and crop yield forecasting at seasonal to multi-decadal timescales. *Environmental Science & Policy*, **12(4)**, 453-465.

Chambers, R. and G.R. Conway, 1992: *Sustainable Rural Livelihoods: Practical Concepts for the 21st Century.* Institute of Development Studies (IDS), IDS, Brighton, UK, 29 pp.

Charles, A., 2011: Human rights and fishery rights in small-scale fisheries management. In *Small-Scale Fisheries Management: Frameworks and Approaches for the Developing World* [Pomeroy, R.S. and N. Andrew (eds.)]. CABI, Wallingford, UK, pp. 59-74.

Chazdon, R.L., 2008: Beyond deforestation: restoring forests and ecosystem services on degraded lands. *Science*, **320(5882)**, 1458-1460.

Chenoweth, J.,P., A. Bruggeman J., Z. Levin, M. Lange, E. Xoplaki, and M. Hadjikakou, 2011: The impact of climate change on the water resources of the eastern Mediterranean and Middle East region: modeled changes and socio-economic implications. *Water Resources Research*, **47(6)**, W06506, doi:10.1029/2010WR010269.

Chindarkar, N., 2012: Gender and climate change-induced migration: proposing a framework for analysis. *Environmental Research Letters*, **7(2)**, 025601, doi:10.1088/1748-9326/7/2/025601.

Chopra, K. and P. Dasgupta, 2008: Assessing the economic and ecosystem services contribution of forests: issues in modelling, and an illustration. *International Forestry Review*, **10(2)**, 376-386.

CIAT, 2010: *Climate Adaptation and Mitigation in the Kenyan Coffee Sector.* Guide Book – Sangana PPP – 4C Climate Module, International Center for Tropical Agriculture (CIAT), Sangana Commodities Ltd., Nairobi, Kenya and The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Bonn, Germany, 42 pp.

CIAT, 2011a: *Future Climate Scenarios for Kenya's Tea Growing Areas.* International Center for Tropical Research (CIAT), Cali, Colombia, 27 pp.

CIAT, 2011b: *Future Climate Scenarios for Uganda's Tea Growing Areas.* Decision and Policy Analyses group (DAPA) at the International Center for Tropical Research (CIAT), Cali, Colombia, 29 pp.

CIAT, 2011c: *Predicting the Impact of Climate Change on the Cocoa-Growing Regions in Ghana and Cote d'Ivoire.* Decision and Policy Analyses group (DAPA) at the International Center for Tropical Agriculture (CIAT), Cali, Colombia, 35 pp.

Cinner, J.E., T.R. McClanahan, T.M. Daw, N.A.J. Graham, J. Maina, S.K. Wilson, and T.P. Hughes, 2009: Linking social and ecological systems to sustain coral reef fisheries. *Current Biology*, **19(3)**, 206-212.

Claessens, L., J.M. Antle, J.J. Stoorvogel, R.O. Valdivia, P.K. Thornton, and M. Herrero, 2012: A method for evaluating climate change adaptation strategies for small-scale farmers using survey, experimental and modeled data. *Agricultural Systems*, **111(0)**, 85-95.

Coe, R. and R.D. Stern, 2011: Assessing and addressing climate-induced risk in sub-Saharan rainfed agriculture: lessons learned. *Experimental Agriculture*, **47**, 395-410.

Cohen, B., 2004: Urban growth in developing countries: a review of current trends and a caution regarding: existing forecasts. *World Development*, **32(1)**, 23-51.

Coles, A.R. and C.A. Scott, 2009: Vulnerability and adaptation to climate change and variability in semi-arid rural southeastern Arizona, USA. *Natural Resources Forum*, **33(4)**, 297-309.

Collier, P., G. Conway, and T. Venables, 2008: Climate change and Africa. *Oxford Review of Economic Policy*, **24(2)**, 337-353.

Collins, T., 2008: The political ecology of hazard vulnerability: marginalization, facilitation and the production of differential risk to urban wildfires in Arizona's White Mountains. *Journal of Political Ecology*, **15(21)**, 21-43.

Connell, D. and Q. Grafton (eds.), 2011: *Basin Futures. Water Reform in the Murray-Darling Basin.* Australia National University (ANU), ANU Press, Canberra, Australia, 500 pp.

Conway, D. and E.L.F. Schipper, 2011: Adaptation to climate change in Africa: challenges and opportunities identified from Ethiopia. *Global Environmental Change*, **21**, 227-237.

Cooke, B. and M. Robles, 2009: *Recent Food Prices Movements: A Time Series Analysis.* IFPRI Discussion Paper No. 00942, International Food Policy Research Institute (IFPRI), Washington, DC, USA, 35 pp.

Cooper, P.J.M., J. Dimes, K.P.C. Rao, B. Shapiro, B. Shiferaw, and S. Twomlow, 2008: Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: an essential first step in adapting to future climate change? *Agriculture, Ecosystems and Environment*, **126**, 24-35.

Cruz, R.V., H. Harasawa, M. Lal, S. Wu, Y. Anokhin, B. Punsalmaa, Y. Honda, M. Jafari, C. Li, and N. Huu Ninh, 2007: Asia. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 469-506.

Cunguara, B. and I. Darnhofer, 2011: Assessing the impact of improved agricultural technologies on household income in rural Mozambique. *Food Policy*, **36(3)**, 378-390.

Damigos, D., 2012: Monetizing the impacts of climate change on the Greek mining sector. *Mitigation and Adaptation Strategies for Global Change*, **17(8)**, 865-878.

Dasgupta, P., 2008: Nature in economics. *Environmental & Resource Economics*, **39(1)**, 1-7.

Dasgupta, P., 2009: Valuation of ecosystem services: methodologies, illustrations and use. In: *Handbook of Environmental Economics in India* [Chopra, K. and V. Dayal (eds.)]. Oxford University Press, New Delhi, India, pp. 137-150.

Dasgupta, P., 2011: The ethics of intergenerational distribution: reply and response to John E. Roemer. *Environmental & Resource Economics*, **50(4)**, 475-493.

Dasgupta, P., D. Bhattacharjee, and A. Kumari, 2013: Socio-economic analysis of climate change impacts on foodgrain production in Indian states. *Environmental Development*, **8**, 5-21.

Dasgupta, S., B. Laplante, C. Meisner, D. Wheeler, and J. Yan, 2009: The impact of sea level rise on developing countries: a comparative analysis. *Climatic Change*, **93(3-4)**, 3-4.

Davies, J. and R. Bennett, 2007: Livelihood adaptation to risk: constraints and opportunities for pastoral development in Ethiopia's afar region. *Journal of Development Studies*, **43(3)**, 490-511.

Dawson, J., E.J. Stewart, H. Lemelin, and D. Scott, 2010: The carbon cost of polar bear viewing in Churchill, Canada. *Journal of Sustainable Tourism*, **18(3)**, 319-336.

de Sherbinin, A., K. Warner, and C. Ehrhart, 2011: Casualties of climate change. *Scientific American*, **304(1)**, 64-71.

Dekens, J., 2008: Local knowledge on flood preparedness: examples from Nepal and Pakistan. In: *Indigenous Knowledge for Disaster Risk Reduction: Good Practices and Lessons Learned from Experiences in the Asia-Pacific Region* [Shaw, R., N. Uy, and J. Baumwoll (eds.)]. European Union (EU), Kyoto University International Environment and Disaster Management Laboratory, Graduate School of Global Environmental Studies, and the United Nations Office for Disaster Risk Reduction – Regional Office for Asia and Pacific (UNISDR AP), UNISDR AP, Bangkok, Thailand, pp. 35-40.

del Río, P. and M. Burguillo, 2008: Assessing the impact of renewable energy deployment on local sustainability: towards a theoretical framework. *Renewable and Sustainable Energy Reviews*, **12(5)**, 1325-1344.

Deltacommissie, 2008: *Working Together with Water. A Living Land Builds for its Future.* Findings of the Deltacommissie, Deltacommissie, The Hague, Netherlands, 138 pp.

Delucchi, M.A., 2010: Impacts of biofuels on climate change, water use, and land use. *Annals of the New York Academy of Sciences*, **1195**, 28-45.

Deressa, T.T., R.M. Hassan, C. Ringler, T. Alemu, and M. Yesuf, 2009: Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia. *Global Environmental Change*, **19**, 248-255.

Desakota Study Team, 2008: *Re-imagining the Rural-Urban Continuum: Understanding the Role Ecosystem Services Play in the Livelihoods of the Poor in Desakota Regions Undergoing Rapid Change.* Research Gap Assessment by the Desakota Study Team, Institute for Social and Environmental Transition-Nepal (ISET-Nepal), Kathmandu, Nepal, 102 pp.

Devendra, C., J. Morton, B. Rischowsky, and D. Thomas, 2005: Livestock systems. In: *Livestock and Wealth Creation: Improving the Husbandry of Livestock Kept by the Poor in Developing Countries* [Owen, E., A. Kitalyi, N. Jayasuriya, and T. Smith (eds.)]. Nottingham University Press, Nottinghamn, UK, pp. 29-52.

Devereux, S., 2009: Why does famine persist in Africa? *Food Security*, **1(1)**, 25-35.
Devine-Wright, P., 2011: *Renewable Energy and the Public: From NIMBY to Participation.* Earthscan, London, UK, and Washington, DC, USA, 336 pp.
Dietz, S., C. Hepburn, and N. Stern, 2007: Economics, ethics and climate change. 20 pp., doi:10.2139/ssrn.1090572.
Dinar, A., R. Hassan, R. Mendelsohn, and J. Benhin, 2008: *Climate Change and Agriculture in Africa: Impact Assessment and Adaptation Strategies*. Earthscan, London, UK and Sterling, VA, USA, 189 pp.
Dockerty, T., A. Lovett, K. Appleton, A. Bone, and G. Sunnenberg, 2006: Developing scenarios and visualisations to illustrate potential policy and climatic influences on future agricultural landscapes. *Agriculture Ecosystems and Environment*, **114(1)**, 103-120.
Döll, P., 2009: Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. *Environmental Research Letters*, **4(3)**, 035006, doi:10.1088/1748-9326/4/3/035006.
Dong S., L. Wen, S. Liu, X. Zhang, J.P. Lassoie, S. Yi, X. Li, J. Li, and Y. Li, 2011: Vulnerability of worldwide pastoralism to global changes and interdisciplinary strategies for sustainable pastoralism. *Ecology and Society*, **16(2)**, 10, www.ecologyandsociety.org/vol16/iss2/art10/.
Dougill, A.J., E.D.G. Fraser, and M.S. Reed, 2010: Anticipating vulnerability to climate change in dryland pastoral systems: using dynamic systems models for the Kalahari. *Ecology and Society*, **15(2)**, 17, www.ecologyandsociety.org/vol15/iss2/art17/.
Dow, K., F. Berkhout, and B.L. Preston, 2013: Limits to adaptation to climate change: a risk approach. *Current Opinion in Environmental Sustainability*, **5(3-4)**, 384-391.
Eakin, H., 2005: Institutional change, climate risk, and rural vulnerability: cases from central Mexico. *World Development*, **33(11)**, 1923-1938.
Eakin, H. and K. Appendini, 2008: Livelihood change, farming, and managing flood risk in the Lerma Valley, Mexico. *Agriculture and Human Values*, **25(4)**, 555-566.
Eakin, H. and L.A. Bojórquez-Tapia, 2008: Insights into the composition of household vulnerability from multicriteria decision analysis. *Global Environmental Change*, **18(1)**, 112-127.
Eakin, H. and A. Patt, 2011: Are adaptation studies effective, and what can enhance their practical impact? *Wiley Interdisciplinary Reviews: Climate Change*, **2(2)**, 141-153.
Eakin, H. and M.B. Wehbe, 2009: Linking local vulnerability to system sustainability in a resilience framework: two cases from Latin America. *Climatic Change*, **93(3-4)**, 355-377.
Eakin, H., L.A. Bojorquez-Tapia, R. Monterde Diaz, E. Castellanos, and J. Haggar, 2011: Adaptive capacity and social-environmental change: theoretical and operational modeling of smallholder coffee systems response in Mesoamerican Pacific Rim. *Environmental Management*, **47(3)**, 352-367.
Easterling, W., P. Aggarwal, P. Batima, K. Brander, L. Erda, M. Howden, A. Kirilenko, J. Morton, J.-F. Soussana, S. Schmidhuber, and F. Tubiello, 2007: Food, fibre and forest products. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 273-313.
Eide, A., 2008: *The Right to Food and the Impact of Liquid Biofuels (Agrofuels).* A Right to Food Study, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 54 pp.
Eliasch, J., 2008: *Climate Change Financing Global Forests: The Eliasch Review*. Earthscan, London, UK and Sterling, VA, USA, 250 pp.
Ellis, F., 2000: *Rural Livelihoods and Diversity in Developing Countries.* 9th edn., Oxford University Press, Oxford, UK, 273 pp.
El-Sadek, A., 2010: Virtual water trade as a solution for water scarcity in Egypt. *Water Resources Management*, **24(11)**, 2437-2448.
Elsasser, H. and P. Messerli, 2001: The vulnerability of the snow industry in the Swiss Alps. *Mountain Research and Development*, **21(4)**, 335-339.
Ensor, J. and R. Berger, 2009: *Understanding Climate Change Adaptation: Lessons from Community-Based Approaches.* Practical Action Publishing, Bourton-on-Dunsmore, UK, 208 pp.
Erenstein, O., K. Sayre, P. Wall, J. Hellin, and J. Dixon, 2012: Conservation agriculture in maize- and wheat-based systems in the (sub)tropics: lessons from adaptation initiatives in South Asia, Mexico, and Southern Africa. *Journal of Susainable Agriculture*, **36(2)**, 180-206.
Ericksen, P., J. de Leeuw, P. Thornton, M. Said, M. Herrero, and A. Notenbaert, 2012: Climate change in sub-Saharan Africa: what consequences for pastoralism? In: *Pastoralism and Development in Africa: Dynamic Change at the Margins* [Catley, A., J. Lind, and I. Scoones (eds.)]. Routledge, London, UK and New York, NY, USA, pp. 71-82.
Eriksen, S.H. and K. O'Brien, 2007: Vulnerability, poverty and the need for sustainable adaptation measures. *Climate Policy*, **7(4)**, 337-352.
Eriksen, S. and J. Lind, 2009: Adaptation as a political process: adjusting to drought and conflict in Kenya's drylands. *Environmental Management*, **43**, 817-835.
Eriksen, S. and J.A. Silva, 2009: The vulnerability context of a savanna area in Mozambique: household drought coping strategies and responses to economic change. *Environmental Science & Policy*, **12(1)**, 33-52.
Ettenger, K., 2012: *Aapuupayuu* (the weather warms up): climate change and the Eeyouch (Cree) of Northern Quebec. In: *Climate Change and Threatened Communities: Vulnerability, Capacity and Action* [Castro, A.P., D. Taylor, and D.W. Brokensha (eds.)]. Practical Action Publishing, Rugby, UK, pp. 107-117
Falloon, P. and R. Betts, 2010: Climate impacts on European agriculture and water management in the context of adaptation and mitigation – the importance of an integrated approach. *Science of the Total Environment*, **408(23)**, 5667-5687.
FAO, 2008: Policy measures taken by governments to reduce the impact of soaring prices. In: *Crop Prospects and Food Situation, No. 3, July 2008*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, pp. 13-17.
FAO, 2010: *Gender and Land Rights Database*. Food and Agriculture Organization of the United Nations (FAO), www.fao.org/gender/landrights/en/.
FAO, 2011: *The State of Food and Agriculture 2010-2011 (SOFA). Women in Agriculture: Closing the Gender Gap for Development*. Food and Agriculture Organization of United Nations (FAO), Rome, Italy, 147 pp.
FAOSTAT, 2013: *FAOSTAT Database.* Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, faostat3.fao.org/faostat-gateway/go/to/home/E.
Farber, S., R. Costanza, D.L. Childers, J. Erickson, K. Gross, M. Grove, C.S. Hopkinson, J. Kahn, S. Pincetl, A. Troy, P. Warren, and M. Wilson, 2006: Linking ecology and economics for ecosystem management. *BioScience*, **56(2)**, 121-133.
Fischlin, A., G.F. Midgley, J.T. Price, R. Leemans, B. Gopal, C. Turley, M.D.A. Rounsevell, O.P. Dube, J. Tarazona, and A.A. Velichko, 2007: Ecosystems, their properties, goods, and services. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 211-272.
Fisher, M., M. Chaudhury, and B. McCusker, 2010: Do forests help rural households adapt to climate variability? Evidence from Southern Malawi. *World Development*, **38(9)**, 1241-1250.
Fleischer, A. and M. Sternberg, 2006: The economic impact of global climate change on Mediterranean rangeland ecosystems: a Space-for-Time approach. *Ecological Economics*, **59(3)**, 287-295.
Forbes, B.C. and T. Kumpula, 2009: The ecological role and geography of reindeer (*Rangifer tarandus*) in northern Eurasia. *Geography Compass*, **3(4)**, 1356-1380.
Ford, J.D., 2009: Sea ice change in Arctic Canada: are there limits to Inuit adaptation? In: *Adapting to Climate Change: Thresholds, Values, and Governance* [Adger, W.N., I. Lorenzoni, and K. L. O'Brien (ed.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 114-128.
Foresight, 2004: *Foresight Future Flooding*. The Foresight Programme, Foresight Flood and Coastal Defence Project, UK Government Office of Science, London, UK, www.bis.gov.uk/foresight/our-work/projects/published-projects/flood-and-coastal-defence/project-outputs/volume-1#sthash.jnpGiEsk.dpuf.
Foresight, 2011: *Migration and Global Environmental Change.* Final Project Report, The Foresight Programme, UK Government Office of Science, London, UK, 236 pp.
Francini-Filho, R.B. and R.L. Moura, 2008: Dynamics of fish assemblages on coral reefs subjected to different management regimes in the Abrolhos Bank, eastern Brazil. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **18(7)**, 1166-1179.
Franco, G., D.R. Cayan, S. Moser, M. Hanemann, and M. Jones, 2011: Second California Assessment: integrated climate change impacts assessment of natural and managed systems. *Climatic Change*, **109(Suppl. 1)**, 1-19.
Fraser, E.D.G., A.J. Dougill, K. Hubacek, C.H. Quinn, J. Sendzimir, and M. Termansen, 2011: Assessing vulnerability to climate change in dryland livelihood systems: conceptual challenges and interdisciplinary solutions. *Ecology and Society*, **16(3)**, 3, www.ecologyandsociety.org/vol16/iss3/art3/.

Furgal, C. and T. Prowse, 2008: Northern Canada. In: *From Impacts to Adaptation: Canada in a Changing Climate 2007* [Lemmen, D.S., F.J. Warren, J. Lacroix, and E. Bush (eds.)]. Government of Canada, Ottawa, ON, Canada, pp. 61-118.

Fürstenau, C., F.W. Badeck, P. Lasch, M.J. Lexer, M. Lindner, P. Mohr, and F. Suckow, 2007: Multiple-use forest management in consideration of climate change and the interests of stakeholder groups. *European Journal of Forest Research*, **126(2)**, 225-239.

Gachathi, F.N. and S. Eriksen, 2011: Gums and resins: The potential for supporting sustainable adaptation in Kenya's drylands. *Climate and Development*, **3(1)**, 59-70.

Gatto, J., B. Kim, P. Mahdavi, H. Namekawa, and H. Tran, 2009: *The Future Impact of Climate Change on the California Wine Industry and Actions the State of California Should Take to Address It.* International Policy Studies Program, Stanford University, Stanford, CA, USA, 52 pp.

Gay, C., F. Estrada, C. Conde, H. Eakin, and L. Villers, 2006: Potential impacts of climate change on agriculture: a case of study of coffee production in Veracruz, Mexico. *Climatic Change*, **79(3-4)**, 259-288.

Gbetibouo, G.A., R.M. Hassan, and C. Ringler, 2010a: Modelling farmers' adaptation strategies for climate change and variability: the case of the Limpopo Basin, South Africa. *Agrekon: Agricultural Economics Research, Policy and Practice in Southern Africa*, **49(2)**, 217-234.

Gbetibouo, G.A., C. Ringler, and R. Hassan, 2010b: Vulnerability of the South African farming sector to climate change and variability: an indicator approach. *Natural Resources Forum*, **34(3)**, 175-187.

Geerts, S. and D. Raes, 2009: Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agricultural Water Management*, **96(9)**, 1275-1284.

Geerts, S., D. Raes, and M. Garcia, 2010: Using AquaCrop to derive deficit irrigation schedules. *Agricultural Water Management*, **98(1)**, 213-216.

Gehrig-Fasel, J., A. Guisan, and N.E. Zimmermann, 2007: Tree line shifts in the Swiss Alps: climate change or land abandonment? *Journal of Vegetation Science*, **18(4)**, 571-582.

Gellrich, M., P. Baur, B. Koch, and N.E. Zimmermann, 2007: Agricultural land abandonment and natural forest re-growth in the Swiss mountains: a spatially explicit economic analysis. *Agriculture, Ecosystems & Environment*, **118(1-4)**, 93-108.

Gellrich, M., P. Baur, B.H. Robinson, and P. Bebi, 2008: Combining classification tree analyses with interviews to study why sub-alpine grasslands sometimes revert to forest: a case study from the Swiss Alps. *Agricultural Systems*, **96(1-3)**, 124-138.

Gemenne, F., 2011: Why the numbers don't add up: a review of estimates and predictions of people displaced by environmental changes. *Global Environmental Change*, **21(Suppl. 1)**, S41-S49.

German, L., G.C. Schoneveld, and P. Pacheco, 2011: The social and environmental impacts of biofuel feedstock cultivation: evidence from multi-site research in the forest frontier. *Ecology and Society*, **16(3)**, 24, www.ecologyandsociety.org/vol16/iss3/art24/.

Ghini, R., E. Hamada, M.J. Pedro Júnior, J.A. Marengo, and R.R.V. Gonçalves, 2008: Risk analysis of climate change on coffee nematodes and leaf miner in Brazil. *Pesquisa Agropecuária Brasileira*, **43(2)**, 187-195.

Giannakopoulos, C., P. Le Sager, M. Bindi, M. Moriondo, E. Kostopoulou, and C.M. Goodess, 2009: Climatic changes and associated impacts in the Mediterranean resulting from a 2 degrees C global warming. *Global and Planetary Change*, **68(3)**, 209-224.

Gilles, J.L., J.L. Thomas, C. Valdivia, and E.S. Yucra, 2013: Laggards or leaders: conservers of traditional agricultural knowledge in Bolivia. *Rural Sociology*, **78(1)**, 51-74.

Girardin, M.P., A.A. Ali, C. Carcaillet, O. Blarquez, C. Hely, A. Terrier, A. Genries, and Y. Bergeron, 2013: Vegetation limits the impact of a warm climate on boreal wildfires. *New Phytologist*, **199(4)**, 1001-1011.

Glaas, E., A. Jonsson, M. Hjerpe, and Y. Andersson-Sköld, 2010: Managing climate change vulnerabilities: formal institutions and knowledge use as determinants of adaptive capacity at the local level in Sweden. *Local Environment*, **15(6)**, 525-539.

Glenn, M., S.H. Kim, J. Ramirez-Villegas, and P. Laderach, 2013: Response of perennial horticultural crops to climate change. *Horticultural Reviews*, **41**, 47-130.

Gold, H.D. and J. Bass, 2010: The energy-water nexus: socioeconomic considerations and suggested legal reforms in the Southwest. *Natural Resources Journal*, **50(3)**, 563-609.

Goulden, M., L.O. Naess, K. Vincent, and W.N. Adger, 2009: Diversification, networks and traditional resource management as adaptations to climate extremes in rural Africa: opportunities and barriers. In: *Adapting to Climate Change: Thresholds, Values and Governance* [Adger, W.N., I. Lorenzoni, and K. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 448-464.

Government of India, 2012: *Implication of Terms Used in Indian Censuses.* Government of India Office of the Registrar, General and Census Commissioner, New Delhi, India, censusindia.gov.in/Data_Products/Library/Indian_perceptive_link/Census_Terms_link/censusterms.html.

Gowdy, J.M., 2008: Behavioral economics and climate change policy. *Journal of Economic Behavior and Organization*, **68(3-4)**, 632-644.

Gray, C. and V. Mueller, 2012: Drought and population mobility in rural Ethiopia. *World Development*, **40(1)**, 134-145.

Green, D., J. Billy, and A. Tapim, 2010: Indigenous Australians' knowledge of weather and climate. *Climatic Change*, **100(2)**, 337-354.

Gurgel, A., J.M. Reilly, and S. Paltsev, 2007: Potential land use implications of global biofuels industry. *Journal of Agricultural & Food Industrial Organization*, **5(2)**, 9, doi:10.2202/1542-0485.1202.

Gyampoh, B.A., M. Idinoba, and S. Amisah, 2008: Water scarcity under a changing climate in Ghana: options for livelihoods adaptation. *Development*, **51**, 415-417.

Haggar, J., 2009: Impact of climate change on coffee farming households in Central America and steps for adaptation in the future. In: *Modelling Agroforestry Systems: Workshop Proceedings, CATIE, 25-29 February, 2008* [Rapidel, B., O. Roupsard, and M. Navarro (eds.)]. CATIE, Turrialba, Costa Rica, pp. 99-104.

Haim, D., M. Shechter, and P. Berliner, 2008: Assessing the impact of climate change on representative field crops in Israeli agriculture: a case study of wheat and cotton. *Climatic Change*, **86(3-4)**, 425-440.

Hall, A., 2012: *Forests and Climate Change: The Social Dimensions of REDD in Latin America.* Edward Elgar Publishing, Cheltenham, UK, 213 pp.

Hall, C.M., 2006: New Zealand tourism entrepreneur attitudes and behaviours with respect to climate change adaptation and mitigation. *International Journal of Innovation and Sustainable Development*, **1(3)**, 229-237.

Hall, S.J., 2011: Climate change and other external drivers in small-scale fisheries: practical steps for responding. In: *Small-Scale Fisheries Management: Frameworks and Approaches for the Developing World* [Pomeroy, R.S. and N. Andrew (eds.)]. CABI Publishing, Wallingford, UK and Cambridge, MA, USA, pp. 132-159.

Hamilton, J.M., D.J. Maddison, and R.S. Tol, 2005: Climate change and international tourism: a simulation study. *Global Environmental Change*, **15(3)**, 253-266.

Hamisi, H.I., M. Tumbo, E. Kalumanga, and P. Yanda, 2012: Crisis in the wetlands: combined stresses in a changing climate – experience from Tanzania. *Climate and Development*, **4(1)**, 5-15.

Hanafi, S., J.C. Mailhol, J.C. Poussin, and A. Zairi, 2012: Estimating water demand at irrigation scheme scales using various levels of knowledge: applications in northern Tunisia. *Irrigation and Drainage*, **61(3)**, 341-347.

Handmer, J., Y. Honda, Z.W. Kundzewicz, N. Arnell, G. Benito, J. Hatfield, I.F. Mohamed, P. Peduzzi, S. Wu, B. Sherstyukov, K. Takahashi, and Z. Yan, 2012: Changes in impacts of climate extremes: human systems and ecosystems. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 231-290.

Hansen, J.W., S.J. Mason, L. Sun, and A. Tall, 2011: Review of seasonal climate forecasting for agriculture in sub-Saharan Africa. *Experimental Agriculture*, **47(2)**, 205-240.

Harvey, P., P. Proudlock, E. Clay, B. Riley, and S. Jaspars, 2010: *Food Aid and Food Assistance in Emergency and Transitional Contexts: A Review of Current Thinking*. A study for the Bundesministerium für Wirtschaftliche Zusammenarbeit und Entwicklung (BMZ), Humanitarian Policy Group, Overseas Development Institute (ODI), London, UK, 94 pp.

Hassan, R., 2010: The double challenge of adapting to climate change while accelerating development in sub-Saharan Africa. *Environment and Development Economics*, **15**, 661-685.

Hassan, R. and C. Nhemachena, 2008: Determinants of African farmers' strategies for adapting to climate change: multinomial choice analysis. *African Journal of Agriculture and Resource Economics*, **2(1)**, 83-104.

Hasting, J.G., 2011: International environmental NGOs and conservation science and policy: a case from Brazil. *Coastal Management*, **39(3)**, 317-335.
Hatcho, N., S. Ochi, and Y. Matsuno, 2010: The evolution of irrigation development in monsoon Asia and historical lessons. *Irrigation and Drainage*, **59(1)**, 4-16.
Headey, D., 2011: Rethinking the global food crisis: the role of trade shocks. *Food Policy*, **36(2)**, 136-146.
Hein, L., M.J. Metzger, and R. Leemans, 2009: The local impacts of climate change in the Ferlo, Western Sahel. *Climatic Change*, **93(3-4)**, 465-483.
Hertel, T.W., M.B. Burke, and D.B. Lobell, 2010: The poverty implications of climate-induced crop yield changes by 2030. *Global Environmental Change*, **20(4)**, 577-585.
Hess J.J., J.N. Malilay, and A.J. Parkinson, 2008: Climate change. The importance of place. *American Journal of Preventive Medicine*, **35(5)**, 468-478.
Hoang, M.H., T.H. Do, M.T. Pham, M. van Noordwijk, and P.A. Minang, 2013: Benefit distribution across scales to reduce emissions from deforestation and forest degradation (REDD+) in Vietnam. *Land use Policy*, **31**, 48-60.
Hoekstra, A.Y. and M.M. Mekonnen, 2012: The water footprint of humanity. *Proceedings of the National Academy of Sciences of the United States of America*, **109(9)**, 3232-3237.
Holder, C.D., 2006: The hydrological significance of cloud forests in the Sierra de las Minas Biosphere Reserve, Guatemala. *Geoforum*, **37(1)**, 82-93.
Hole, D.G., B. Huntley, J. Arinaitwe, S.H.M. Butchart, Y.C. Collingham, L.D.C. Fishpool, D.J. Pain, and S.G. Willis, 2011: Toward a management framework for networks of protected areas in the face of climate change. *Conservation Biology*, **25(2)**, 305-315.
Holt-Gimenez, E., 2002: Measuring farmers' agroecological resistance after hurricane Mitch in Nicaragua: a case study in participatory, sustainable land management impact monitoring. *Agriculture Ecosystems & Environment*, **93(1-3)**, 87-105.
Horton, G., L. Hanna, and B. Kelly, 2010: Drought, drying and climate change: emerging health issues for ageing Australians in rural areas. *Australasian Journal on Ageing*, **29(1)**, 2-7.
Huang, H., M. von Lampe, and F. van Tongeren, 2011: Climate change and trade in agriculture. *Food Policy*, **36(Suppl. 1)**, S9-S13.
Huber, U., H.K.M. Bugman, and M.A. Reasoner (eds.), 2005: *Global Change and Mountain Regions*. An Overview of Current Knowledge Series: Advances in Global Change Research, Vol. 23, Springer, Dordrecht, Netherlands, 650 pp.
Huisman, H., 2005: Contextualising chronic exclusion: female-headed households in semi-arid Zimbabwe. *Tijdschrift Voor Economische en Sociale Geografie*, **96(3)**, 253-263.
Huntjens, P., L. Lebel, C. Pahl-Wostl, J. Camkin, R. Schulze, and N. Kranz, 2012: Institutional design propositions for the governance of adaptation to climate change in the water sector. *Global Environmental Change*, **22(1)**, 67-88.
IFAD, 2010: *Rural Poverty Report 2011. New Realities, New Challenges: New Opportunities For Tomorrow's Generation.* The International Fund for Agricultural Development (IFAD), IFAD, Rome, Italy, 319 pp.
Iglesias, A., R. Mougou, M.Q. Moneo and S. Quiroga, 2010: Towards adaptation of agriculture to climate change in the Mediterranean. *Regional Environmental Change*, **11(Suppl. 1)**, 159-196.
Immerzeel, W.W., L.P.H. Van Beek, and M.F.P. Bierkens, 2010: Climate change will affect the Asian water towers. *Science*, **328(5984)**, 1382-1385.
Ingold, K., J. Balsiger, and C. Hirschi, 2010: Climate change in mountain regions: how local communities adapt to extreme events. *Local Environment*, **15(7)**, 651-661.
IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)], Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.
Jaramillo, J., E. Muchugu, F.E. Vega, A. Davis, C. Borgemeister, and A. Chabi-Olaye, 2011: Some like it hot: the influence and implications of climate change on coffee berry borer (*Hypothenemus hampei*) and coffee production in East Africa. *Plos One*, **6(9)**, e24528, doi:10.1371/journal.pone.0024528.
Jones, C.R. and J.R. Eiser, 2010: Understanding 'local' opposition to wind development in the UK: how big is a backyard? *Energy Policy*, **38(6)**, 3106-3117.
Jones, G.V., M.A. White, O.R. Cooper, and K. Storchman, 2005: Climate change and global wine quality. *Climatic Change*, **73(3)**, 319-343.
Jones, L. and E. Boyd, 2011: Exploring social barriers to adaptation: insights from Western Nepal. *Global Environmental Change: Human and Policy Dimensions*, **21(4)**, 1262-1274.
Jones, P.G. and P.K. Thornton, 2009: Croppers to livestock keepers: livelihood transitions to 2050 in Africa due to climate change. *Environmental Science & Policy*, **12(4)**, 427-437.
Juana, J.S., K.M. Strzepek, and J.F. Kirsten, 2008: Households' welfare analyses of the impact of global change on water resources in South Africa. *Agrekon*, **47(3)**, 309-326.
Kabat, P., L.O. Fresco, J. Marcel, F. Stive, C.P. Veerman, J.S.L.J. van Alphen, B.W.A.H. Parmet, W. Hazeleger, and C.A. Katsman, 2009: Dutch coasts in transition. *Nature Geosciences*, **2**, 450-452.
Kabubo-Mariara, J., 2008: Climate change adaptation and livestock activity choices in Kenya: an economic analysis. *Natural Resources Forum*, **32**, 131-141.
Kabubo-Mariara, J., 2009: Global warming and livestock husbandry in Kenya: impacts and adaptations. *Ecological Economics*, **68(7)**, 1915-1924.
Kahinda, J.M., A.E. Taigbenu, and R.J. Boroto, 2010: Domestic rainwater harvesting as an adaptation measure to climate change in South Africa. *Physics and Chemistry of the Earth*, **35**, 742-751.
Karapinar, B., 2011: Export restrictions and the WTO law: how to reform the 'regulatory deficiency'. *Journal of World Trade*, **45(6)**, 1139-1155.
Karapinar, B., 2012: Defining the legal boundaries of export restrictions: a case law analysis. *Journal of International Economic Law*, 1-37, doi:10.1093/jiel/jgs021.
Karapinar, B. and C. Häberli, 2010: *Food Crises and the WTO: World Trade Forum.* Cambridge University Press, Cambridge, UK, and New York, NY, USA, 365 pp.
Kashaigili, J.J., K. Rajabu, and P. Masolwa, 2009: Freshwater management and climate change adaptation: experiences from the Great Ruaha River catchment in Tanzania. *Climate and Development*, **1(3)**, 220-228.
Kennet, M., 2009: The costs of women's unequal pay and opportunity: transforming the unbalanced structure of our economy to meet the challenges of today: climate change, poverty and the twin crises of the economy and economics. *International Journal of Green Economics*, **3(2)**, 107-129.
Kiem, A. and E. Austin, 2013. Drought and the future of rural communities: opportunities and challenges for climate change adaptation in regional Victoria, Australia. *Global Environmental Change*, **23(5)**, 1307-1316.
Kim, S., 2010: Fisheries development in northeastern Asia in conjunction with changes in climate and social systems. *Marine Policy*, **34(4)**, 803-809.
Kirshen, P., K. Knee, and M. Ruth, 2008: Climate change and coastal flooding in Metro Boston: impacts and adaptation strategies. *Climatic Change*, **90**, 453-473.
Klein, R.J.T., S. Huq, F. Denton, T.E. Downing, R.G. Richels, J.B. Robinson, and F.L. Toth, 2007: Inter-relationships between adaptation and mitigation. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (ed.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 745-777.
Klemm, O., R.S. Schemenauer, A. Lummerich, P. Cereceda, V. Marzol, D. Corell, J. van Heerden, D. Reinhard, T. Gherezghiher, J. Olivier, P. Osses, J. Sarsour, E. Frost, M.J. Estrela, J.A. Valiente, and G.M. Fessehaye, 2012: Fog as a fresh-water resource: overview and perspectives. *Ambio*, **41(3)**, 221-34.
Klijn, F., N. Asselman, and H. Van der Most, 2009: Compartmentalisation: flood consequence reduction by splitting up larger polder areas. *Journal of Flood Risk Managment*, **3**, 3-17.
Klint L.M., E. Wong, M. Jiang, T. Delacy, D. Harrison, and D. Dominey-Howes, 2012a: Climate change adaptation in the Pacific Island tourism sector: analysing the policy environment in Vanuatu. *Current Issues in Tourism*, **15(3)**, 247-274.
Klint L.M., M. Jiang, A. Law, T. DeLacy, S. Filep, E. Calgaro, D. Dominey-Howes, and D. Harrison, 2012b: Dive tourism in Luganville, Vanuatu: shocks, stressors, and vulnerability to climate change. *Tourism in Marine Environments*, **8(1-2)**, 91-109.
Klopper, E., C.H. Vogel, and W.A. Landman, 2006: Seasonal climate forecasts – potential agricultural-risk management tools? *Climatic Change*, **76**, 73-90.
Kniveton, D., C. Smith, and S. Wood, 2011: Agent-based model simulations of future changes in migration flows for Burkina Faso. *Global Environmental Change: Human and Policy Dimensions*, **21(Suppl. 1)**, S34-S40.
Knüppe, K., 2011: The challenges facing sustainable and adaptive groundwater management in South Africa. *Water SA*, **37(1)**, 67-79.
Kokic, P., R. Nelson, H. Meinke, A. Potgieter, and J. Carter, 2007: From rainfall to farm incomes – transforming advice for Australian drought policy. I. Development and testing of a bioeconomic modelling system. *Australian Journal of Agricultural Research*, **58(10)**, 993-1003.
Kosoy, N. and E. Corbera, 2010: Payments for ecosystem services as commodity fetishism. *Ecological Economics*, **69(6)**, 1228-1236.

Kotir, J.H., 2011: Climate change and variability in sub-Saharan Africa: a review of current and future trends and impacts on agriculture and food security. *Environment, Development and Sustainability*, **13(3)**, 587-605.

Kranz, N., T. Menniken, and J. Hinkel, 2010: Climate change adaptation strategies in the Mekong and Orange-Senqu basins: what determines the state-of-play? *Environmental Science & Policy*, **13(7)**, 648-649.

Krätli, S., C. Huelsebusch, S. Brooks, and B. Kaufmann, 2013: Pastoralism: a critical asset for food security under global climate change. *Animal Frontiers*, **3(1)**, 42-50.

Kristjanson, P., A. Waters-Bayer, N. Johnson, A. Tipilda, J. Njuki, I. Baltenweck, D. Grace, and S. MacMillan, 2010: *Livestock and Women's Livelihoods: A Review of the Recent Evidence.* Discussion Paper No. 20, International Livestock Research Institute (ILRI), ILRI, Nairobi, Kenya, 30 pp.

Krysanova, V., C. Dickens, J. Timmerman, C. Varela-Ortega, M. Schlueter, K. Roest, P. Huntjens, F. Jaspers, H. Buiteveld, E. Moreno, J.d.P. Carrera, R. Slamova, M. Martinkova, I. Blanco, P. Esteve, K. Pringle, C. Pahl-Wostl, and P. Kabat, 2010: Cross-comparison of climate change adaptation strategies across large river basins in Europe, Africa and Asia. *Water Resources Management*, **24(14)**, 4121-4160.

Kuik, O., B. Buchner, M. Catenacci, A. Goria, E. Karakaya, and R.S.J. Tol, 2008: Methodological aspects of recent climate change damage cost studies. *Integrated Assessment*, **8(1)**, 19-40.

Kumar, A., 2010: *A Review of Human Development Trends in South Asia: 1990-2009*. Human Development Reports Research Paper No. 2010/44, United Nations Development Programme (UNDP), New York, NY, USA, 52 pp.

Kumssa, A. and J.F. Jones, 2010: Climate change and human security in Africa. *International Journal of Sustainable Development and World Ecology*, **17(6)**, 453-461.

Kundzewicz, Z.W. and P. Döll, 2009: Will groundwater ease freshwater stress under climate change? *Hydrological Sciences Journal*, **54(4)**, 665-675.

Kundzewicz, Z.W., L.J. Mata, N.W. Arnell, P. Döll, B. Jimenez, K. Miller, T. Oki, Z. Sen, and I. Shiklomanov, 2008: The implications of projected climate change for freshwater resources and their management. *Hydrological Sciences Journal*, **53(1)**, 3-10.

Kurz W.A., C.C. Dymond, G. Stinson, G.J. Rampley, E.T. Neilson, A.L. Carroll, L. Safranyik, and T. Ebata, 2008: Mountain pine beetle and forest carbon feedback to climate change. *Nature*, **452(7190)**, 987-990.

Laderach, P., J. Haggar, C. Lau, A. Eitzinger, O. Ovalle, M. Baca, A. Jarvis, and M. Lundy, 2010: *Mesoamerican Coffee: Building a Climate Change Adaptation Strategy.* CIAT Policy Brief, International Center for Tropical Agriculture (CIAT), CIAT, Cali, Colombia, 4 pp.

Laderach, P., A. Martínez-Valle, G. Schroth, and N. Castro, 2013: Predicting the future climate suitability for cocoa farming of the world's leading producer countries, Ghana and Cote de'Ivoire. *Climatic Change*, **119(3-4)**, 841-854.

Lal, P., J. Alavalapati, and E. Mercer, 2011: Socio-economic impacts of climate change on rural United States. *Mitigation and Adaptation Strategies for Global Change*, **(7)**, 1381-2386.

Lama, S. and B. Devkota, 2009: Vulnerability of mountain communities to climate change and adaptation strategies. *Journal of Agriculture and Environment*, **10**, 76-83.

Lambrou, Y. and G. Paina, 2006: *Gender: The Missing Component of the Response to Climate Change.* Food and Agriculture Organization of the United Nations (FAO), FAO, Rome, Italy, 44 pp.

Lane, M.E., P.H. Kirshen, and R.M. Vogel, 1999: Indicators of impacts of global climate change on U.S. water resources. *Journal of Water Resources Planning and Management*, **125(4)**, 194-204.

Langyintuo, A.S. and C. Mungoma, 2008: The effect of household wealth on the adoption of improved maize varieties in Zambia. *Food Policy*, **33(6)**, 550-559.

Larsen, P., S. Goldsmith, O. Smith, M. Wilson, K. Strzepek, P. Chinowsky, and B. Saylor, 2008: Estimating future costs for Alaska public infrastructure at risk from climate change. *Global Environmental Change*, **18(3)**, 442-457.

Larson, K., D.C. Ibes, and D.D. White, 2011: Gendered perspectives about water risks and policy strategies: a tripartite conceptual approach. *Environment and Behaviour*, **43(3)**, 415-438.

Latif, M. and N.S. Keenlyside, 2009: El Niño/Southern Oscillation response to global warming. *Proceedings of the National Academy of Sciences of the United States of America*, **106(49)**, 20578-20583.

Leach, M., R. Mearns, and I. Scoones, 1999: Environmental entitlements: dynamics and institutions in community-based natural resource management. *World Development*, **27(2)**, 225-247.

Lefale, P., 2010: *Ua 'afa le Aso* Stormy weather today: traditional ecological knowledge of weather and climate. The Samoa experience. *Climatic Change*, **100(2)**, 317-335.

Lemmen, D.S., F.J. Warren, J. Lacroix, and E. Bush (eds.), 2008: *From Impacts to Adaptation: Canada in a Changing Climate 2007.* Government of Canada, Ottawa, ON, Canada, 448 pp.

Lerner, A.M. and H. Eakin, 2010: An obsolete dichotomy? Rethinking the rural? Urban interface in terms of food security and production in the global south. *Geographical Journal*, **177(4)**, 311-320.

Lerner, A.M., H. Eakin, and S. Sweeney, 2013: Understanding pen-urban maize production through an examination of household livelihoods in the Toluca Metropolitan Area, Mexico. *Journal of Rural Studies*, **30**, 52-63.

Lin, B.B., 2011: Resilience in agriculture through crop diversification: adaptive management for environmental. *BioScience*, **61(3)**, 183-193.

Lin, E., X. Yang, S. Ma, H. Ju, L. Guo, W. Xiong, Y. Li, and Y. Xu, 2005: Case Study 1: China benefiting from global warming: agricultural production in Northeast China. *IDS Bulletin*, **36(4)**, 15-32.

Linne, K., 2011: *4C Climate Code: Additional*, *Verifiable*, *Voluntary. Climate Change Adaptation and Mitigation in the Kenyan Coffee Sector.* Sangana Public-Private-Partnership (Sangana PPP): Sangana Commodities Ltd, the German Technical Cooperation (GIZ), Common Code for the Coffee Community (4C) Association, Tchibo GmbH, and the World Bank, Sangana PPP, Nairobi, Kenya and GIZ, Bonn, Germany, 15 pp.

Linnerooth-Bayer, J. and R. Mechler, 2007: Disaster safety nets for developing countries: extending public-private partnerships. *Environmental Hazards*, **7(1)**, 54-61.

Lioubimtseva, E. and G.M. Henebry, 2009: Climate and environmental change in arid Central Asia: impacts, vulnerability, and adaptations. *Journal of Arid Environments*, **73(11)**, 963-977.

Little, P.D., H. Mahmoud, and D.L. Coppock, 2001: When deserts flood: risk management and climatic processes among East African pastoralists. *Climate Research*, **19**, 149-159.

Lobell, D.B., W. Schlenker, and J. Costa-Roberts, 2011: Climate trends and global crop production since 1980. *Science Science*, **333(6042)**, 616-620.

Lobell, D.B., C.B. Field, K.N. Cahill, and C. Bonfils, 2006: Impacts of future climate change on California perennial crop yields: model projections with climate and crop uncertainties. *Agricultural and Forest Meteorology*, **141(2-4)**, 208-218.

Lobell, D.B. and C.B. Field, 2011: California perennial crops in a changing climate. *Climatic Change*, **109**, 317-333.

Locatelli, B., V. Rojas, and Z. Salinas, 2008: Impacts of payments for environmental services on local development in northern Costa Rica: a fuzzy multi-criteria analysis. *Forest Policy and Economics*, **10(5)**, 275-285.

López-i-Gelats, F., 2013: Is mountain farming no longer viable? In: *The Future of Mountain Agriculture* [Mann, S. (ed.)]. Springer Geography, Berlin, Germany, pp. 89-104.

López-i-Gelats, F., J.D. Tàbara, and J. Bartolomé, 2009: The rural in dispute: discourses of rurality in the Pyrenees. *Geoforum*, **40(4)**, 602-612.

López-i-Gelats, F., M.J. Milán, and J. Bartolomé, 2011: Is farming enough in mountain areas? Farm diversification in the Pyrenees. *Land use Policy*, **28(4)**, 783-791.

Lotze-Campen, H., A. Popp, T. Beringer, C. Müller, A. Bondeau, S. Rost, and W. Lucht, 2010: Scenarios of global bioenergy production: the trade-offs between agricultural expansion, intensification and trade. *Ecological Modelling*, **221(18)**, 2188-2196.

Love, T. and A. Garwood, 2011: Wind, sun and water: complexities of alternative energy development in rural northern Peru. *Rural Society*, **20(3)**, 294-307.

Luzar, J.B., K.M. Silvius, H. Overman, S.T. Giery, J.M. Read, and J.M.V. Fragoso, 2011: Large-scale environmental monitoring by indigenous peoples. *BioScience*, **61(10)**, 771-781.

Lyon B. and Dewitt D.G., 2012: A recent and abrupt decline in the East African long rains. *Geophysical Research Letters*, **39(2)**, doi:10.1029/2011GL050337.

MacDonald, A., R. Calow, D. MacDonald, W.G. Darling, and B.E.O. Dochartaigh, 2009: What impact will climate change have on rural groundwater supplies in Africa? *Hydrological Sciences Journal*, **54(4)**, 690-703.

MacDonald, G.M., 2010: Water, climate change, and sustainability in the southwest. *Proceedings of the National Academy of Sciences of the United States of America*, **107(50)**, 21256-21262.

Magrin, G.O., M.I. Travasso, G.R. Rodríguez, S. Solman, and M. Núñez, 2009: Climate change and wheat production in Argentina. *International Journal of Global Warming*, **1(1)**, 214-226.

Marsden, T., 1999: Rural futures: the consumption countryside and its regulation. *Sociologia Ruralis*, **39(4)**, 501-526.

Marshall A., 2012: Existing agbiotech traits continue global march. *Nature Biotechnology*, **30(3)**, 207, doi:10.1038/nbt.2154.

Mawdsley, J.R., R. O'Malley, and D.S. Ojima, 2009: A review of climate-change adaptation strategies for wildlife management and biodiversity conservation. *Conservation Biology*, **23(5)**, 1080-1089.

Mbow, C., O. Mertz, A. Diouf, K. Rasmussen, and A. Reenberg, 2008: The history of environmental change and adaptation in eastern Saloum-Senegal – driving forces and perceptions. *Global and Planetary Change*, **64(3-4)**, 210-221.

McGee T.G, 1991: The emergence of *desakota* regions in Asia: expanding a hypothesis. In: *The Extended Metropolis: Settlement Transition in Asia* [Ginsburg, N., B. Koppel, and T.G. McGee (eds.)]. University of Hawaii Press, Honolulu, HI, pp. 3-26.

McIntyre, B.D., H.R. Herren, J. Wakhungu, and R.T. Watson, 2009: *International Assessment of Agricultural Knowledge, Science and Technology for Development: Global Report.* Island Press, Washington, DC, USA, 590 pp.

McIntyre, S. and T.P. Duane, 2011: Water, work, wildlife, and wilderness: the collaborative federal public lands planning framework for utility-scale solar energy development in the desert Southwest. *Environmental Law*, **41**, 1093-1189.

McLeman, R.A., 2011: Settlement abandonment in the context of global environmental change. *Global Environmental Change: Human and Policy Dimensions*, **21(Suppl. 1)**, S108-S120.

McLeman, R.A. and L.M. Hunter, 2010: Migration in the context of vulnerability and adaptation to climate change: insights from analogues. *Wiley Interdisciplinary Reviews: Climate Change*, **1(3)**, 450-461.

McLeman, R.A. and B. Smit, 2006: Vulnerability to climate change hazards and risks: crop and flood insurance. *The Canadian Geographer*, **50(2)**, 217-226.

McSweeney, K. and O.T. Coomes, 2011: Climate-related disaster opens a window of opportunity for rural poor in northeastern Honduras. *Proceedings of the National Academy of Sciences of the United States of America*, **108(13)**, 5203-5208.

MDBA, 2011: *Proposed Basin Plan: A Draft for Consultation.* MDBA Publication No. 192/11, Draft plan prepared for the Commonwealth of Australia by the Murray-Darling Basin Authority (MDBA), Australian Government, MDBA, Canberra City, ACT, Australia, 210 pp.

Meinke, H. and R. Stone, 2005: Seasonal and inter-annual climate forecasting: the new tool for increasing preparedness to climate variability and change in agricultural planning and operations. *Climatic Change*, **70(1-2)**, 221-253.

Mendelsohn, R. and M. Reinsborough, 2007: A Ricardian analysis of US and Canadian farmland. *Climatic Change*, **81(1)**, 9-17.

Mendelsohn, R., A. Basist, P. Kurukulasuriya, and A. Dinar, 2007: Climate and rural income. *Climatic Change*, **81(1)**, 101-118. **Mendelsohn**, R., P. Christensen, and J. Arellano-Gonzalez, 2010: A Ricardian analysis of Mexican farms. *Environment and Development Economics*, **15(2)**, 153-171.

Mertz, O., K. Halsnaes, J.E. Olesen, and K. Rasmussen, 2009a: Adaptation to climate change in developing countries. *Environmental Management*, **43(5)**, 743-752.

Mertz, O., C. Mbow, A. Reenberg, and A. Diouf, 2009b: Farmers' perceptions of climate change and agricultural adaptation strategies in rural Sahel. *Environmental Management*, **43(5)**, 804-816.

Mertz, O., C. Mbow, J.O. Nielsen, A. Maiga, D. Diallo, A. Reenberg, A. Diouf, B. Barbier, I.B. Moussa, M. Zorom, I. Ouattara, and D. Dabi, 2010: Climate factors play a limited role for past adaptation strategies in West Africa. *Ecology and Society*, **15(4)**, 25, www.ecologyandsociety.org/vol15/iss4/art25/.

Mertz, O., C. Mbow, A. Reenberg, L. Genesio, E.F. Lambin, S. D'haen, M. Zorom, K. Rasmussen, D. Diallo, B. Barbier, I. Bouzou Moussa, A. Diouf, J.Ø. Nielsen, and I. Sandholt, 2011: Adaptation strategies and climate vulnerability in the Sudano-Sahelian region of West Africa. *Atmospheric Science Letters*, **12**, 104-108.

Meyer, D., 2006: Caribbean tourism, local sourcing and enterprise development: review of the literature. *Current Issues in Tourism*, **10(6)**, 558-583.

Meza, F.J. and D. Silva, 2009: Dynamic adaptation of maize and wheat production to climate change. *Climatic Change*, **94(1-2)**, 143-156.

Meza, F., D. Wilks, L. Gurovich, and N. Bambach, 2012: Impacts of climate change on irrigated agriculture in the Maipo Basin, Chile: reliability of water rights and changes in the demand for irrigation. *Journal of Water Resources Planning and Management*, **138(5)**, 421-430.

Mideksa, T.K., 2010: Economic and distributional impacts of climate change: the case of Ethiopia. *Global Environmental Change: Human and Policy Dimensions*, **20(2)**, 278-286.

Midgley, G.F., L. Hannah, D. Millar, M.C. Rutherford, and L.W. Powrie, 2002: Assessing the vulnerability of species richness to anthropogenic climate change in a biodiversity hotspot. *Global Ecology and Biogeography*, **11(6)**, 445-451.

Millner, A. and R. Washington, 2011: What determines perceived value of seasonal climate forecasts? A theoretical analysis. *Global Environmental Change*, **21(1)**, 209-218.

Mills, D.J., L. Westlund, G. de Graaf, Y. Kura, R. Willman, and K. Kelleher, 2011: Under-reported and undervalued: small-scale fisheries in the developing world. In: *Small-Scale Fisheries Management: Frameworks and Approaches for the Developing World* [Pomeroy, R.S. and N. Andrew (eds.)]. CABI, Wallingford, UK and Cambridge, MA, USA, pp. 1-15.

Ministry of Construction, 1993. *Town Planning Standard: GB 50188-93*. Ministry of Construction, People's Republic of China, Beijing, China, www.upo.gov.cn/pages/zwgk/fgzc/bz/2464.shtml.

Moench, M. and D. Gyawali, 2008: *Final Report Desakota, Part II A. Reinterpreting the Urban-Rural Continuum. Conceptual Foundations for Understanding the Role Ecosystem Services Play in the Livelihoods of the Poor in Regions Undergoing Rapid Change.* Research for Development Document, Department for International Development (DFID), DFID, London, UK, 27 pp.

Molnar, J.J., 2010: Climate change and societal response: livelihoods, communities, and the environment. *Rural Sociology*, **75(1)**, 1-16.

Molua, E.L., 2009: An empirical assessment of the impact of climate change on smallholder agriculture in Cameroon. *Global and Planetary Change*, **67(3-4)**, 205-208.

Montagnini, F. and C. Finney, 2011: Payments for environmental services in latin america as a tool for restoration and rural development. *Ambio*, **40(3)**, 285-297.

Montenegro, A. and R. Ragab, 2010: Hydrological response of a Brazilian semi-arid catchment to different land use and climate change scenarios: a modelling study. *Hydrological Processes*, **24(19)**, 2705-2723.

Morton, J., 2006: Pastoralist coping strategies and emergency livestock market intervention. In: *Pastoral Livestock Marketing in Eastern Africa: Research and Policy Challenges* [McPeak, J.G. and P.D. Little (eds.)]. ITDG Publications, Bourton-on-Dunsmore, UK, pp. 227-246.

Morton, J.F., 2007: The impact of climate change on smallholder and subsistence agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, **104(50)**, 19680-19685.

Mougou, R., M. Mansour, A. Iglesias, R.Z. Chebbi, and A. Battaglini, 2011: Climate change and agricultural vulnerability: a case study of rain-fed wheat in Kairouan, Central Tunisia. *Regional Environmental Change*, **11(Suppl. 1)**, S137-S142.

Moumouni, I. and L. Idrissou, 2013a: *Innovation Systems for Agriculture and Climate in Benin: An Inventory* [Morton, J. (trans.)]. Climate Learning for African Agriculture Working Paper No. 3, African Forum for Agricultural Advisory Services (AFAAS), Forum for Agricultural Research in Africa (FARA), and Natural Resources Institute (NRI), University of Greenwich, NRI, Kent, UK, 24 pp.

Moumouni, I. and L. Idrissou, 2013b: *Innovation Systems for Agriculture and Climate in Benin: Analysis of Three Case-Studies from Benin.* Climate Learning for African Agriculture Working Paper No.5 [Morton, J. and P. Govinden (trans.)]. African Forum for Agricultural Advisory Services (AFAAS), Forum for Agricultural Research in Africa (FARA), and Natural Resources Institute (NRI), University of Greenwich, NRI, Kent, UK, 23 pp.

Mukheibir, P., 2008: Water resources management strategies for adaptation to climate-induced impacts in South Africa. *Water Resources Management*, **22**, 1259-1276.

Müller, A., J. Schmidhuber, J. Hoogeveen, and P. Steduto 2008: Some insights in the effect of growing bio-energy demand on global food security and natural resources. *Water Policy*, **10(Suppl. 1)**, 83-94.

Müller, C., W. Cramer, W.L. Hare, and H. Lotze-Campen, 2011: Climate change risks for African agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, **108(11)**, 4313-4315.

Naab, J.B. and H. Koranteng, 2012: *Gender and Climate Change Research Results: Jirapa, Ghana.* Working Paper No. 17, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Nairobi, Kenya, 23 pp.

Naess, L.O., 2013: The role of local knowledge in adaptation to climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **4(2)**, 99-106.

Nakashima, D.J., K.G. McLean, H.D. Thulstrup, A.R. Castillo, and J.T. Rubis, 2012: *Weathering Uncertainty: Traditional Knowledge for Climate Change Assessment and Adaptation.* United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris, France and United Nations University (UNU), Darwin, Australia, 120 pp.

Nazlioglu, S., C. Erdem, and U. Soytas, 2013: Volatility spillover between oil and agricultural commodity markets. *Energy Economics*, **36**, 658-665.

Nearing, M.A., F.F. Pruski, and M.R. O'Neal, 2004: Expected climate change impacts on soil erosion rates: a review. *Journal of Soil and Water Conservation*, **59(1)**, 43-50.

Nelson, A. and K.M. Chomitz, 2011: Effectiveness of strict vs. multiple use protected areas in reducing tropical forest fires: a global analysis using matching methods. *Plos One*, **6(8)**, e22722, doi:10.1371/journal.pone.0022722.

Nelson, G.C., M.W. Rosegrant, J. Koo, R. Robertson, T. Sulser, T. Zhu, C. Ringler, S. Msangi, A. Palazzo, M. Batka, M. Magalhaes, R. Valmonte-Santos, M. Ewing, and D. Lee, 2009a: *Climate Change: Impact on Agriculture and Costs of Adaptation.* International Food Policy Research Institute (IFPRI), Washington, DC, USA, 19 pp.

Nelson, G., A. Palazzo, C. Ringler, T. Sulser, and M. Batka, 2009b: *The Role of International Trade in Climate Change Adaptation.* ICTSD-IPC Platform on Climate Change, Agriculture and Trade, Issue Paper No.4, International Centre for Trade and Sustainable Development and International Food (ICTSD) and International Food and Agricultural Trade Policy Council (IPC), ICTSD, Geneva, Switzerland and IPC, Washington, DC, USA, 16 pp.

Nelson, G.C., M.W. Rosegrant, A. Palazzo, I. Gray, C. Ingersoll, R. Robertson, S. Tokgoz, T. Zhu, T.B. Sulser, C. Ringler, S. Msangi, and L. You, 2010: *Food Security, Farming, and Climate Change to 2050: Scenarios, Results, Policy Options.* IFPRI Research Monograph, Washington, DC, USA, 130 pp.

Nelson, G.C., H. Valin, R.D. Sands, P. Havlik, H. Ahammad, D. Deryng, J. Elliott, S. Fujimori, T. Hasegawa, E. Heyhoe, P. Kyle, M. Von Lampe, H. Lotze-Campen, D.M. d'Croz, H. van Meijl, D. van der Mensbrugghe, C. Müller, A. Popp, R. Robertson, S. Robinson, E. Schmid, C. Schmitz, A. Tabeau, and D. Willenbockel, 2013: Climate change effects on agriculture: economic responses to biophysical shocks. *Proceedings of the National Academy of Sciences of the United States of America* (in press), doi:10.1073/pnas.1222465110.

Nelson, J.A., 2008: Economists, value judgments, and climate change: a view from feminist economics. *Ecological Economics*, **65(3)**, 441-447.

Nelson, R., P. Kokic, and H. Meinke, 2007: From rainfall to farm incomes – transforming advice for Australian drought policy. II. Forecasting farm incomes. *Australian Journal of Agricultural Research*, **58(10)**, 1004-1012.

Nelson, V. and T. Stathers, 2009: Resilience, power, culture, and climate: a case study from semi-arid Tanzania, and new research directions. *Gender & Development*, **17(1)**, 81-94.

Nelson, V., K. Meadows, T. Cannon, J. Morton, and A. Martin, 2002: Uncertain predictions, invisible impacts, and the need to mainstream gender in climate change adaptations. *Gender and Development*, **10(2)**, 51-59.

Nepal, S.K., 2008: Tourism-induced rural energy consumption in the Annapurna region of Nepal. *Tourism Management*, **29(1)**, 89-100.

Neumayer, E. and T. Pluemper, 2007: The gendered nature of natural disasters: the impact of catastrophic events on the gender gap in life expectancy, 1981-2002. *Annals of the Association of American Geographers*, **97(3)**, 551-566.

Newsham, A.J. and D.S.G. Thomas, 2011: Knowing, farming and climate change adaptation in North-Central Namibia. *Global Environmental Change*, **21(2)**, 761-770.

Ngoundo, M., C.E. Kan, Y.C. Chang, S.L. Tsai, and I. Tsou, 2007: Options for water saving in tropical humid and semi-arid regions using optimum compost application rates. *Irrigation and Drainage*, **56(1)**, 87-08.

Nielsen, J.Ø. and A. Reenberg, 2010: Cultural barriers to climate change adaptation: a case study from northern Burkina Faso. *Global Environmental Change*, **20**, 142-152.

Nielsen, J.Ø., S. D'haen, and A. Reenberg, 2012: Adaptation to climate change as a development project: a case study from northern Burkina Faso. *Climate and Development*, **4(1)**, 16-25.

Nkem, J.N., R. Munang, and B. Jallow, 2011: Decentralizing solutions for rural water supply under climate impacts in sub-Saharan Africa. *Environment: Science and Policy for Sustainable Development*, **53(2)**, 14-17.

Nogués-Bravo, D., M.B. Araújo, M.P. Errea, and J.P. Martínez-Rica, 2007: Exposure of global mountain systems to climate warming during the 21st Century. *Global Environmental Change*, **17(3-4)**, 420-428.

NRC, 2008: *Potential Impacts of Climate Change on U.S. Transportation.* Transportation Research Board Special Report 290, Transportation Research Board, Washington, DC, USA, 280 pp.

Nyaupane, G. and N. Chhetri, 2009: Vulnerability to climate change of nature-based tourism in the Nepalese Himalayas. *Tourism Geographies*, **11(1)**, 95-119.

Nyaupane, G.P. and S. Poudel, 2011: Linkages among biodiversity, livelihood, and tourism. *Annals of Tourism Research*, **38(4)**, 1344-1366.

Nyong, A., F. Adesina, and B. Osman Elasha, 2007: The value of indigenous knowledge in climate change mitigation and adaptation strategies in the African Sahel. *Mitigation and Adaptation Strategies for Global Change*, **12**, 787-797.

O'Farrell, P.J., P.M.L. Anderson, S.J. Milton, and W.R.J. Dean, 2009: Human response and adaptation to drought in the arid zone: lessons from southern Africa. *Southern African Journal of Science*, **105**, 34-39.

Obioha, E.E., 2008: Climate change, population drift and violent conflict over land resources in northeastern Nigeria. *Journal of Human Ecology*, **23(3)**, 311-324.

O'Brien, K., R. Leichenko, U. Kelkar, H. Venema, G. Aandahl, H. Tompkins, A. Javed, S. Bhadwal, S. Barg, L. Nygaard, and J. West, 2004: Mapping vulnerability to multiple stressors: climate change and globalization in India. *Global Environmental Change*, **14(4)**, 303-313.

O'Brien, K., S. Eriksen, L.P. Nygaard, and A. Schjolden, 2007: Why different interpretations of vulnerability matter in climate change discourses. *Climate Policy*, **7(1)**, 73-88.

O'Brien, K., T. Quinlan, and G. Ziervogel, 2009: Vulnerability interventions in the context of multiple stressors: lessons from the Southern Africa Vulnerability Initiative (SAVI). *Environmental Science & Policy*, **12(1)**, 23-32.

OECD, 2006: *The New Rural Paradigm: Policies and Governance.* Organisation for Economic Co-operation and Development (OECD), OECD, Paris, France, 155 pp.

OECD and FAO, 2013: *OECD – FAO Agricultural Outlook 2013-2022: Highlights.* Organisation for Economic Co-operation and Development (OECD) and Food and Agriculture Organization of the United Nations (FAO), OECD, Paris, France and FAO, Rome, Italy, 116 pp.

Ogawa-Onishi Y., P.M. Berry, and N. Tanaka, 2010: Assessing the potential impacts of climate change and their conservation implications in Japan: a case study of conifers. *Biological Conservation*, **143(7)**, 1728-1736.

Olesen, J.E., M. Trnka, K.C. Kersebaum, A.O. Skjelvåg, B. Seguin, P. Peltonen-Sainio, F. Rossi, J. Kozyra, and F. Micale, 2011: Impacts and adaptation of European crop production systems to climate change. *European Journal of Agronomy*, **34(2)**, 96-112.

Oluoko-Odingo, A.A., 2011: Vulnerability and adaptation to food insecurity and poverty in Kenya. *Annals of the Association of American Geographers*, **101(1)**, 1-20.

Omolo, N., 2011: Gender and climate change-induced conflict in pastoral communities: case study of Turkana in northwestern Kenya. *African Journal on Conflict Resolution*, **10(2)**, 81-102.

Orlove, B., 2009: The past, present and some possible futures of adaptation. In: *Adapting to Climate Change. Thresholds, Values, Governance* [Adger, W.N., I. Lorenzoni, and K.L. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK, pp. 131-164.

Osbahr, H., C. Twyman, N.W. Adger, and D.S.G. Thomas, 2008: Effective livelihood adaptation to climate change disturbance: scale dimensions of practice in Mozambique. *Geoforum*, **39(6)**, 1951-1964.

Paavola, J., 2008: Livelihoods, vulnerability and adaptation to climate change in Morogoro, Tanzania. *Environmental Science & Policy*, **11(7)**, 642-654.

Parks, B.C. and J.T. Roberts, 2006: Globalization, vulnerability to climate change, and perceived injustice. *Society & Natural Resources*, **19(4)**, 337-355.

Parnell, S. and R. Walawege, 2011: Sub-Saharan African urbanisation and global environmental change. *Global Environmental Change*, **21(Suppl. 1)**, S12-S20.

Patt, A.G. and D. Schröter, 2008: Perceptions of climate risk in Mozambique: implications for the success of adaptation strategies. *Global Environmental Change*, **18(3)**, 458-467.

Patt, A., N. Peterson, M. Carter, M. Velez, U. Hess, and P. Suarez, 2009: Making index insurance attractive to farmers. *Mitigation and Adaptation Strategies for Global Change*, **14(8)**, 737-753.

Patt, A., P. Suarez, and U. Hess, 2010: How do small-holder farmers understand insurance, and how much do they want it? Evidence from Africa. *Global Environmental Change*, **20(1)**, 153-161.

Patterson, T.M., V. Niccolucci, and S. Bastianoni, 2007: Beyond "more is better": ecological footprint accounting for tourism and consumption in Val di Merse, Italy. *Ecological Economics*, **62(3-4)**, 747-756.

Payet, R. and W. Agricole, 2006: Climate change in the Seychelles: implications for water and coral reefs. *Ambio*, **35(4)**, 182-189.

Pearce, T.D., J.D. Ford, J. Prno, F. Duerden, J. Pittman, M. Beaumier, L. Berrang-Ford, and B. Smit, 2011: Climate change and mining in Canada. *Mitigation and Adaptation Strategies for Global Change*, **16(3)**, 347-368.

Peterson, N.D., K. Broad, B. Orlove, C. Roncoli, R. Taddei, and M. Velez, 2010: Participatory processes and climate forecast use: socio-cultural context, discussion, and consensus. *Climate and Development*, **2(1)**, 14-29.

Phadke, R., 2011: Resisting and reconciling big wind: middle landscape politics in the New American West. *Antipode*, **43(3)**, 754-776.

Phelps, J., E.L. Webb, and A. Agrawal, 2010: Does REDD+ threaten to recentralize forest governance? *Science*, **328(5976)**, 312-313.

Pinto, H. and E. Assad, 2008: *Global Warming and the New Geography of Agricultural Production in Brazil.* The British Embassy, Brasília, Brazil, 42 pp.

Pinto, H.S., J. Zullo Jr., E.D. Assad, and B.A. Evangelista, 2007: O aquecimento global e a cafeicultura brasileira. *Boletim da Sociedade Brasileira de Meteorologia*, **31**, 65-72.

Plevin, R.J., M. O'Hare, A.D. Jones, M.S. Torn, and H.K. Gibbs, 2010: Greenhouse gas emissions from biofuels' indirect land use change are uncertain but may be much greater than previously estimated. *Environmental Science & Technology*, **44(1)**, 8015-8021.

PNCC, 2007: *Vulnerabilidad y Adaptación al Cambio Climático en Bolivia. Resultados de un Proceso de Investigación Participativa en las Regiones del Lago Titicaca y Los Valles Cruceños.* The República de Bolivia, Ministerio de Planificación del Desarrollo, Programa Nacional de Cambios Climáticos (PNCC) and ETC-International with support from the Netherlands Ministry of Foreign Affairs, PNCC, La Paz, Bolivia, 141 pp.

Porter-Bolland, L., E.A. Ellis, M.R. Guariguata, I. Ruiz-Mallén, S. Negrete-Yankelevich, and V. Reyes-García, 2012: Community managed forests and forest protected areas: an assessment of their conservation effectiveness across the tropics. *Forest Ecology and Management*, **268**, 6-17.

Potter, R.B., 2000: *The Urban Caribbean in an Era of Global Change*. Ashgate, Aldershot, UK, 208 pp.

Power, M., 2009: Global climate policy and climate justice: a feminist social provisioning approach. *Challenge*, **52(1)**, 47-66.

Prados, M., 2010: Renewable energy policy and landscape management in Andalusia, Spain: the facts. *Energy Policy*, **38(11)**, 6900-6909.

Pramova, E., B. Locatelli, H. Djoudi, and O.A. Somorin, 2012: Forests and trees for social adaptation to climate variability and change. *Wiley Interdisciplinary Reviews: Climate Change*, **3(6)**, 581-596.

Preston, B.L., R. Suppiah, I. Macadam, and J. Bathols, 2006: *Climate Change in the Asia Pacific Region: A Consultancy Report Prepared for the Climate Change and Development Roundtable.* The Commonwealth Scientific and Industrial Research Organisation (CSIRO) Marine and Atmospheric Research, CSIRO, Aspendale, Australia, 89 pp.

Pretty, J., C. Toulmin, and S. Williams, 2011: Sustainable intensification in African agriculture. *International Journal of Agricultural Sustainability*, **9(1)**, 5-24.

Productivity Commission, 2009: *Government Drought Support.* Final Inquiry Report No. 46, Productivity Commission, Melbourne, Australia, 431 pp.

Quiroga, A. and C. Gaggioli, 2010: Condiciones para el desarrollo de producciones agrícolas-ganaderas en el S.O. Bonaerense. Panel suelos: gestión del agua y viabilidad de los sistemas productivos. *Anales de la Academia Nacional de Agronomía y Veterinaria de la República Argentina*, **LXIV**, 233-249.

Raleigh, C., L. Jordan, and I. Salehyan, 2008: *Assessing the Impact of Climate Change on Migration and Climate.* Commissioned by the World Bank Group for the Social Dimensions of Climate Change Workshop March 5-6, Social Development, The World Bank, Washington, DC, USA, 49 pp.

Ramirez-Villegas, J.M., A. Salazar, C. Jarvis, and E. Navarro-Racines, 2012: A way forward on adaptation to climate change in Colombian agriculture: perspectives towards 2050. *Climatic Change*, **115(3-4)**, 611-628.

Rao, K.P.C., W.G. Ndegwa, K. Kizito, and A. Oyoo, 2011: Climate variability and change: farmer perceptions and understanding of intra-seasonal variability in rainfall and associated risk in semi-arid Kenya. *Experimental Agriculture*, **47(2)**, 267-291.

Rasmussen, K., W. May, T. Birk, M. Mataki, O. Mertz, and D. Yee, 2009: Climate change on three Polynesian outliers in the Solomon Islands: impacts, vulnerability and adaptation. *Geografisk Tidsskrift – Danish Journal of Geography*, **109(1)**, 1-13.

Ravallion, M., S. Chen, and P. Sangraula, 2007: New evidence on the urbanization of global poverty. *Population and Development Review*, **33(4)**, 667-701.

Reardon, T., J. Berdegué, C.B. Barrett, and K. Stamoulis, 2007: Household income diversification into rural nonfarm activities. In: *Transforming the Rural Nonfarm Economy: Opportunities and Threats in the Developing World* [Haggblade, S., P.B.R. Hazell, and T. Reardon (eds.)]. Johns Hopkins University, Baltimore, MD, USA, pp. 115-140.

Rees, W.G., F.M. Stammler, F.S. Danks, and P. Vitebsky, 2008: Vulnerability of European reindeer husbandry to global change. *Climatic Change*, **87(1-2)**, 199-217.

Reid, H., L. Sahlen, J. Stage, and J. MacGregor, 2008: Climate change impacts on Namibia's natural resources and economy. *Climate Policy*, **8(5)**, 452-466.

Reid, P. and C. Vogel, 2006: Living and responding to multiple stressors in South Africa – glimpses from KwaZulu-Natal. *Global Enivronmental Change*, **16(2)**, 195-206.

Reidsma, P., T. Tekelenburg, M. van den Berg, and R. Alkemade, 2006: Impacts of land-use change on biodiversity: an assessment of agricultural biodiversity in the European Union. *Agriculture Ecosystems & Environment*, **114(1)**, 86-102.

Reimer, J.J. and M. Li, 2009: Yield variability and agricultural trade. *Agricultural and Resource Economics Review*, **38**, 258-270.

Reynolds, J.F., D.M.S. Smith, E.F. Lambin, B.L. Turner, M. Mortimore, S.P.J. Batterbury, T.E. Downing, H. Dowlatabadi, R.J. Fernandez, J.E. Herrick, E. Huber-Sannwald, H. Jiang, R. Leemans, T. Lynam, F.T. Maestre, M. Ayarza, and B. Walker, 2007: Global desertification: building a science for dryland development. *Science*, **316(5826)**, 847-851.

Ribas, A., J. Calbo, A. Llausas, and J.A. Lopez-Bustins, 2010: Climate change at the local scale: trends, impacts and adaptations in a Northwestern Mediterranean Region (Costa Brava, NE Iberian Peninsula). *International Journal of Climate Change: Impacts and Responses*, **2(1)**, 247-264.

Ribot, J., 2010: Vulnerability does not fall from the sky: towards multi-scale pro-poor climate policy. In: *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World* [Mearns, R. and N. Norton (eds.)]. The World Bank, Washington, DC, USA, pp. 47-57.

Rijkers, B. and R. Costa, 2012: Gender and rural non-farm entrepreneurship. *World Development*, **40(12)**, 2411-2426.

Ringler, C., 2010: Climate change and hunger: Africa's smallholder farmers struggle to adapt. *EuroChoices*, **9(3)**, 16-21.

Rivera-Ferre, M.G. and F. López-i-Gelats, 2012: *The Role of Small Scale Livestock Farming in Climate Change and Food Security.* Vétérinaires Sans Frontières Europa (VSF-Europe), Brussels, Belgium, 146 pp.

Rivera-Ferre, M.G., M. Ortega-Cerdà, and J. Baumgärtner, 2013a: Rethinking study and management of agricultural systems for policy design. *Sustainability Science*, **5(9)**, 3858-3875.

Rivera-Ferre, M.G., M. Di Masso, M. Mailhost, F. López-i-Gelats, D. Gallar, I. Vara, and M. Cuellar, 2013b: *Understanding the Role of Local and Traditional Agricultural Knowledge in a Changing World Climate: The Case of the Indo-Gangetic Plains.* CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), a collaboration of the Consultative Group on International Agricultural Research (CGIAR) and the Earth System Science Partnership (ESSP), Frederiksberg, Denmark, 98 pp.

Robledo, C., N. Clot, A. Hammill, and B. Riché, 2011: The role of forest ecosystems in community-based coping strategies to climate hazards: three examples from rural areas in Africa. *Forest Policy and Economics*, **24**, 20-28.

Rochdane, S., B. Reichert, M. Messouli, A. Babqiqi, and M.Y. Khebiza, 2012: Climate change impacts on water supply and demand in Rheraya Watershed (Morocco), with potential adaptation strategies. *Water*, **4(1)**, 28-44.

Rodrigues, R.R., S. Gandolfi, A.G. Nave, J. Aronson, T.E. Barreto, C.Y. Vidal, and P.H.S. Brancalion, 2011: Large-scale ecological restoration of high-diversity tropical forests in SE Brazil. *Forest Ecology and Management*, **261(10)**, 1605-1613.

Romsdahl, R.J., L. Atkinson, and J. Schultz, 2013: Planning for climate change across the US Great Plains: concerns and insights from government decision-makers. *Journal of Environmental Studies and Sciences*, **3(1)**, 1-14.

Roncoli, C., K. Ingram, and P. Kirshen, 2001: The costs and risks of coping with drought: livelihood impacts and farmers' responses in Burkina Faso. *Climate Research*, **19(2)**, 119-132.

Roncoli, C., C. Jost, P. Kirshen, M. Sanon, K. Ingram, M. Woodin, L. Somé, F. Ouattara, B. Sanfo, C. Sia, P. Yaka, and G. Hoogenboom, 2009: From accessing to assessing forecasts: an end-to-end study of participatory climate forecast dissemination in Burkina Faso (West Africa). *Climatic Change*, **92(3)**, 433-460.

Rounsevell, M.D., I. Reginster, M.B. Araujo, T.R. Carter, N. Dendoncker, F. Ewert, J.I. House, S. Kankaanpaa, R. Leemans, and M.J. Metzger, 2006: A coherent set of future land use change scenarios for Europe. *Agriculture, Ecosystems and Environment*, **114(1)**, 57-68.

Ruel, M.T., J.L. Garrett, C.R. Hawkes, and M.C. Cohen, 2010: The food, fuel, and financial crises affect the urban and rural poor disproportionately: a review of the evidence. *The Journal of Nutrition*, **140(Suppl. 1)**, 170S-176S.

Safranyik, L. and B. Wilson, 2006: *The Mountain Pine Beetle: A Synthesis of Biology, Management, and Impacts on Lodgepole Pine.* Canadian Forest Service, Pacific Forestry Centre, Victoria, BC, Canada, 303 pp.

Saldaña-Zorrilla, S., 2008: Stakeholder´s views in reducing rural vulnerability to natural disasters in Southern Mexico. *Global Environmental Change*, **18(4)**, 583-597.

Salema, H.B., H.C. Norman, A. Nefzaoui, D.E. Mayberry, K.L. Pearce, and D.K. Revell, 2010: Potential use of oldman saltbush (*Atriplex nummularia* Lindl.) in sheep and goat feeding. *Small Ruminant Research*, **91**, 13-28.

Sall, D.M., D.S.M. Tall, D.A. Tandia, A. Samb, A.K. Sano, and S. Sylla, 2010: *International Migration, Social Change and Local Governance in Ourossogui and Louga, Two Small Urban Centres in Senegal*. Human Settlements Working Paper Series, Rural-Urban Interactions and Livelihood Strategies Working Paper 23, International Institute for Environment and Development (IIED), London, UK, 41 pp.

Sallu, S.M., C. Twyman, and L.C. Stringer, 2010: Resilient or vulnerable livelihoods? Assessing livelihood dynamics and trajectories in rural Botswana. *Ecology and Society*, **15(4)**, 3, www.ecologyandsociety.org/vol15/iss4/art3/.

SAN, 2011: *SAN Climate Module: Criteria for Mitigation and Adaptation to Climate Change*. Sustainable Agriculture Network (SAN), San José, Costa Rica, 15 pp.

Sanghi A. and Mendelsohn R., 2008: The impacts of global warming on farmers in Brazil and India. *Global Environmental Change*, **18(4)**, 655-665.

Schepp, K., 2010: *How Can Small-Scale Coffee and Tea Producers Adapt to Climate Change.* AdapCC Final Report – Results & Lessons Learnt, Cafédirect and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, GTZ, Eschborn, Germany, 37 pp.

Schmidhuber, J. and I. Matuschke, 2010: Shift and swing factors and the special role of weather and climate. In: *Food Crises and the WTO: World Trade Forum* [Karapinar, B. and C. Häberli (eds.)]. Cambridge University Press, Cambridge, New York, NY, USA, pp. 135-164.

Schmitz, C., A. Biewald, H. Lotze-Campen, A. Popp, J.P. Dietrich, B. Bodirsky, M. Krause, and I. Weindl, 2012: Trading more food: implications for land use, greenhouse gas emissions, and the food system. *Global Environmental Change*, **22(1)**, 189-209.

Schroth, G., P. Laderach, J. Dempewolf, S. Philpott, J. Haggar, H. Eakin, T. Castillejos, J.G. Moreno, L.S. Pinto, R. Hernandez, A. Eitzinger, and J. Ramirez-Villegas, 2009: Towards a climate change adaptation strategy for coffee communities and ecosystems in the Sierra Madre de Chiapas, Mexico. *Mitigation and Adaptation Strategies for Global Change*, **14(7)**, 605-625.

Scott, D., G. McBoyle, A. Minogue, and B. Mills, 2006: Climate change and the sustainability of ski-based tourism in eastern North America: a reassessment. *Journal of Sustainable Tourism*, **14(4)**, 376-398.

Scott, D., B. Jones, and J. Konopek, 2007: Implications of climate and environmental change for nature-based tourism in the Canadian Rocky Mountains: a case study of Waterton Lakes National Park. *Tourism Management*, **28(2)**, 570-579.

Scott, D., S. Gössling, and C.M. Hall, 2012: International tourism and climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **3(3)**, 213-232.

SEI, 2009: *The Economics of Climate Change in Kenya.* Final Report Submitted in Advance of COP15, Stockholm Environment Institute (SEI) Oxford Office, Oxford, UK, 65 pp.

Seneviratne, S.I., N. Nicholls, D. Easterling, C.M. Goodess, S. Kanae, J. Kossin, Y. Luo, J. Marengo, K. McInnes, M. Rahimi, M. Reichstein, A. Sorteberg, C. Vera, and X. Zhan, 2012: Changes in climate extremes and their impacts on the natural physical environment. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 109-230.

Seo, S.N., 2010: Is an integrated farm more resilient against climate change? A micro-econometric analysis of portfolio diversification in African agriculture. *Food Policy*, **35(1)**, 32-40.

Seo, S.N. and R. Mendelsohn, 2007a: *Climate Change Adaptation in Africa: A Microeconomic Analysis of Livestock Choice.* World Bank Policy Research Working Paper 4277, The World Bank, Washington, DC, USA, 39 pp.

Seo, S.N. and R. Mendelsohn, 2007b: *The Impact of Climate Change on Livestock Management in Africa: A Structural Ricardian Analysis.* Policy Research Working Paper 4603, The World Bank Development Research Group, Sustainable Rural and Urban Development Team, The World Bank,Washington, DC, USA, 48 pp.

Seo, S.N. and R. Mendelsohn, 2008: A Ricardian analysis of the impact of climate change on South American farms. *Chilean Journal of Agricultural Research*, **68(1)**, 69-79.

Seto, K.C., 2011: Exploring the dynamics of migration to mega-delta cities in Asia and Africa: contemporary drivers and future scenarios. *Global Environmental Change*, **21(Suppl. 1)**, S94-S107.

Sheate, W.R., M.R. do Partidário, H. Byron, O. Bina, and S. Dagg, 2008: Sustainability assessment of future scenarios: methodology and application to mountain areas of Europe. *Environmental Managment*, **41(2)**, 282-299.

Sietz, D., M.K.B. Lüdeke, and C. Walther, 2011: Categorisation of typical vulnerability patterns in global drylands. *Global Environmental Change*, **21(2)**, 431-440.

Sikor, T., J. Stahl, T. Enters, J.C. Ribot, N. Singh, W.D. Sunderlin, and L. Wollenberg, 2010: REDD-plus, forest people's rights and nested climate governance. *Global Environmental Change*, **20(3)**, 423-425.

Silva, J.A., S. Eriksen, and Z.A. Ombe, 2010: Double exposure in Mozambique's Limpopo River Basin. *Geographical Journal*, **176(1)**, 6-24.

Simelton, E., E.D.G. Fraser, M. Termansen, P.M. Forster, and A.J. Dougill, 2009: Typologies of crop-drought vulnerability: an empirical analysis of the socio-economic factors that influence the sensitivity and resilience to drought of three major food crops in China (1961-2001). *Environmental Science & Policy*, **12(4)**, 438-452.

Simon, D., 2008: Urban environments: issues on the peri-urban fringe. *Annual Review of Environmental Resources*, **33**, 167-185.

Simon, D., D. McGregor , and D. Thompson, 2006: Contemporary perspectives on the peri-urban zones of cities in developing countries. In: *The Peri-Urban Interface: Approaches to Sustainable Natural and Human Resource Use* [McGregor, D., D. Simon, and D. Thompson (eds.)]. Earthscan, London, UK, pp. 3-17.

Simonett, O., 2006: Impact of temperature rise on robusta coffee in Uganda. Web document in collection: COP 5 Emission graphics, UNEP/GRID-Arendal, www.grida.no/graphicslib/detail/impact-of-temperature-rise-on-robusta-coffee-in-uganda_0520.

Singh, S.P., I. Bassignana-Khadka, B.S. Karky, and E. Sharma, 2011: *Climate Change in the Hindu Kush Himalayas: The State of Current Knowledge.* International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal, 88 pp.

Smart, R.E., 2010: A lump of coal, a bunch of grapes. *Journal of Wine Research*, **21(2)**, 107-111.

Smucker, T.A. and B. Wisner, 2008: Changing household responses to drought in Tharaka, Kenya: vulnerability, persistence and challenge. *Disasters*, **32(2)**, 190-205.

Sowers, J., A. Vengosh, and E. Weinthal, 2011: Climate change, water resources, and the politics of adaptation in the Middle East and North Africa. *Climatic Change*, **104**, 599-627.

Spangenberg, J.H. and J. Settele, 2010: Precisely incorrect? Monetising the value of ecosystem services. *Ecological Complexity*, **7(3)**, 327-337.

Speranza, C.I., B. Kiteme, P. Ambenje, U. Wiesmann, and S. Makali, 2010: Indigenous knowledge related to climate variability and change: insights from droughts in semi-arid areas of former Makueni District, Kenya. *Climatic Change*, **100(2)**, 295-315.

Speranza, C.I., 2013: Buffer capacity: capturing a dimension of resilience to climate change in African smallholder agriculture. *Regional Environmental Change*, **13(3)**, 521-535.

Stage, J., 2010: Economic valuation of climate change adaptation in developing countries. *Annals of the New York Academy of Sciences*, **1185(1)**, 150-163.

Stathers, T., R. Lamboll, and B.M. Mvumi, 2013: Postharvest agriculture in a changing climate: its importance to African smallholder farmers. *Food Security*, **5(3)**, 361-392.

Statistical Institute of Jamaica, 2012: *Population and Housing Census: Findings*. Statistical Institute of Jamaica, Kingston, Jamaica, 150 pp. http://jamaica-gleaner.com/pages/population-and-housing-census-2011/files/assets/basic-html/toc.html.

Stern, N., 2007: *The Economics of Climate Change: The Stern Review.* Cambridge University Press, Cambridge, UK, 712 pp.

Stringer, L.C., J.C. Dyer, M.S. Reed, A.J. Dougill, C. Twyman, and D. Mkwambisi, 2009: Adaptations to climate change, drought and desertification: local insights to enhance policy in southern Africa. *Environmental Science and Policy*, **12**, 748-765.

Stuart-Hill, S.I. and R.E. Schulze, 2010: Does South Africa's water law and policy allow for climate change adaptation? *Climate and Development*, **2(2)**, 128-144.

Suarez, P. and J. Linnerooth-Bayer, 2010: Micro-insurance for local adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, **1(2)**, 271-278.

Sukhija, B.S., 2008: Adaptation to climate change: strategies for sustaining groundwater resources during droughts. In: *Climate Change and Groundwater* [Drangoni, W. and B.S. Sukhija (eds.)]. Geological Society Special Publications, London, UK, pp. 169-181.

Swiss Re, 2009: *The Effects of Climate Change: An Increase in Coastal Flood Damage in Northern Europe.* Swiss Reinsurance Company Ltd. (Swiss Re), Swiss Re, Zurich, Switzerland, 4 pp.

Tacoli, C., 2009: Crisis or adaptation? Migration and climate change in a context of high mobility. *Environment and Urbanization*, **21(2)**, 513-525.

Tall, A., S.J. Mason, M. van Aalst, P. Suarez, Y. Ait-Chellouche, A.A. Diallo, and L. Braman, 2012: Using seasonal climate forecasts to guide disaster management: the Red Cross experience during the 2008 west Africa floods. *International Journal of Geophysics*, 986016, doi:10.1155/2012/986016.

Tamiotti, L., R. Teh, V. Kulaçoğlu, A. Olhoff, B. Simmons, and H. Abaza, 2009: *Trade and Climate Change.* World Trade Organization (WTO) and United Nations Environment Programme (UNEP), WTO, Geneva, Switzerland, 166 pp.

Tanaka, T. and N. Hosoe, 2011: Does agricultural trade liberalization increase risks of supply-side uncertainty? Effects of productivity shocks and export restrictions on welfare and food supply in Japan. *Food Policy*, **36(3)**, 368-377.

Tandon, N., 2007: Biopolitics, climate change and water security: impact, vulnerability and adaptation issues for women. *Agenda: Women for Gender Equity*, *Special Issue: Biopolitics*, **21(73)**, 4-17.

Tefera, T., 2012: Post-harvest losses in African maize in the face of increasing food shortage. *Food Security*, **4(2)**, 267-277.

Terrier, A., M.P. Girardin, C. Perie, P. Legendre, and Y. Bergeron, 2013: Potential changes in forest composition could reduce impacts of climate change on boreal wildfires. *Ecological Applications*, **23(1)**, 21-35.

Thomas, D.S.G., C. Twyman, H. Osbahr, and B. Hewitson, 2007: Adaptation to climate change and variability: farmer responses to intra-seasonal precipitation trends in South Africa. *Climatic Change*, **83(3)**, 301-322.

Thomas, R.J., 2008: Opportunities to reduce the vulnerability of dryland farmers in Central and West Asia and North Africa to climate change. *Agriculture, Ecosystems and Environment*, **126**, 36-45.

Thornton, P.K., J. van de Steeg, A. Notenbaert, and M. Herrero, 2009: The impacts of climate change on livestock and livestock systems in developing countries: a review of what we know and what we need to know. *Agricultural Systems*, **101(3)**, 113-127.

Thuiller, W., O. Broennimann, G. Hughes, M. Alkemade, G.F. Midgley, and F. Corsie, 2006: Vulnerability of African mammals to anthropogenic climate change under conservative land transformation assumptions. *Global Change Biology*, **12(3)**, 424-440.

Thurlow, J. and P. Wobst, 2003: *Poverty-Focused Social Accounting Matrices for Tanzania.* TMD Discussion Papers No. 112, International Food Policy Research Institute (IFPRI), Washington, DC, USA, 59 pp.

Thurlow, J., T. Zhu, and X. Diao, 2009: *The Impact of Climate Variability and Change on Economic Growth and Poverty in Zambia.* IFPRI Discussion Paper 00890, International Food Policy Research Institute (IFPRI), Washington, DC, USA, 62 pp.

Timmer, C.P., 2010: Reflections on food crises past. *Food Policy*, **35(1)**, 1-11.

Tischbein, B., A.M. Manschadi, A.K. Hornidge, C. Conrad, J.P.A. Lamers, L. Oberkircher, G. Schorcht, and P.L.G. Vlek, 2011: Proposals for the more efficient utilization of water resources in the Province of Khorezm, Uzbekistan. *Hydrologie und Wasserbewirtschaftung*, **55(2)**, 116-125.

Tol, R.S.J., T.E. Downing, O.J. Kuik, and J.B. Smith, 2004: Distributional aspects of climate change impacts. *Global Environmental Change: Human and Policy Dimensions*, **14(3)**, 259-272.

Tompkins, E.L., R. Few, and K. Brown, 2008: Scenario-based stakeholder engagement: incorporating stakeholders preferences into coastal planning for climate change. *Journal of Environmental Management*, **88(4)**, 1580-1592.

Toth, F.L. and E. Hizsnyik, 2008: Managing the inconceivable: participatory assessments of impacts and responses to extreme climate change. *Climatic Change*, **91(1-2)**, 81-101.

Tran, P., F. Marincioni, and R. Shaw, 2010: Catastrophic flood and forest cover change in the Huong river basin, central Viet Nam: a gap between common perceptions and facts. *Journal of Environmental Management*, **91(11)**, 2186-2200.

Traore, S., T. Owiyo, and Y. Sokona, 2013: Dirty drought causing loss and damage in Northern Burkina Faso. *International Journal of Global Warming*, **5(4)**, 498-513.

Tschakert, P., 2007: Views from the vulnerable: understanding climatic and other stressors in the Sahel. *Global Environmental Change*, **17(3-4)**, 381-396.

Tyler, S. and L. Fajber, 2009: *Land and Water Resource Management in Asia: Challenges for Climate Adaptation.* Background Paper for the Asia Regional Meeting, "Dialogue on Climate Change Adaptation for Land and Water Management," January 19 – 21, 2009, Hanoi, Vietnam, International Institute for Sustainable Development (IISD), IISD, Winnipeg, Canada, 24 pp.

Tyler, N.J.C., J.M. Turi, M.A. Sundset, K. Strøm Bull, M.N. Sara, E. Reinert, N. Oskal, C. Nellemann, J.J. McCarthy, S.D. Mathiesen, M.L. Martello, O.H. Magga, G.K. Hovelsrud, I. Hanssen-Bauer, N.I. Eira, I.M.G. Eira, and R.W. Corell, 2007: Saami reindeer pastoralism under climate change: applying a generalized framework for vulnerability studies to a sub-arctic social–ecological system. *Global Environmental Change*, **17(2)**, 191-206.

Ulimwengu, J.M., Workneh,S. and P. Zelekawork, 2009: *Impact of Soaring Food Price in Ethiopia: Does Location Matter?* IFPRI Discussion Paper 00846, International Food Policy Research Center (IFPRI), IFPRI, Washington, DC, USA, 24 pp.

UN DESA Population Division, 2010: *World Urbanization Prospects. The 2009 Revision: Highlights.* United Nations, Department of Economic and Social Affairs (UN DESA) Population Division, New York, NY, USA, 45 pp.

UN DESA Population Division, 2013: *World Population Prospects: The 2012 Revision*, *Highlights and Advance Tables.* United Nations, Department of Economic and Social Affairs (UN DESA) Population Division Working Paper No. ESA/P/WP.228. UN DESA Population Division, New York, NY, USA, 94 pp.

UN ECLAC, 2010a: *The Economics of Climate Change in Central America – Summary 2010.* United Nations Economic Commission for Latin America and the Caribbean (UN ECLAC), Santiago, Chile, 144 pp.

UN ECLAC, 2010b: *Economics of Climate Change in Latin America and the Caribbean – Summary 2010.* United Nations Economic Commission for Latin America and the Caribbean (UN ECLAC), Santiago, Chile, 107 pp.

UNEP, 2009: *Climate and Trade Policies in a Post-2012 World.* United Nations Environment Programme (UNEP), Geneva, Switzerland, 95 pp.

Urcola, H.A., J.H. Elverdin, M.A. Mosciaro, C. Albaladejo, J.C. Manchado, and J.F. Giussepucci, 2010: Climate change impacts on rural societies: stakeholders perceptions and adaptation strategies in Buenos Aires, Argentina. In: *Innovation and Sustainable Development in Agriculture and Food – ISDA 2010*, Montepellier, France, hal.archives-ouvertes.fr/hal-00522176.

Vaghefi, N., M. Nasir Shamsudin, A. Makmom, and M. Bagheri, 2011: The economic impact of climate change on the rice production in Malaysia. *International Journal of Agricultural Research*, **6(1)**, 67-74.

Valdivia, C., A. Seth, J.L. Gilles, M. García, E. Jiménez, J. Cusicanqui, F. Navia, and E. Yucra, 2010: Adapting to climate change in Andean ecosystems: landscapes, capitals, and perceptions shaping rural livelihood strategies and linking knowledge systems. *Annals of the Association of American Geographers*, **100(4)**, 818-834.

van de Giesen, N., J. Liebe, and G. Jung, 2010: Adapting to climate change in the Volta Basin, West Africa. *Current Science*, **98(8)**, 1033-1037.

Van der Geest, K., 2011: North-South migration in Ghana: what role for the environment? *International Migration*, **49(S1)**, e69-e94.

Van der Geest, K. and R. De Jeu, 2008: Climate change and displacement: Ghana. *Forced Migration Review*, **(31)**, 16.

van der Horst, D., 2007: NIMBY or not? Exploring the relevance of location and the politics of voiced opinions in renewable energy siting controversies. *Energy Policy*, **35(5)**, 2705-2714.

Van Noordwijk, M., F. Agus, S. Dewi, A. Ekadinata, H.L. Tata, Suyanto, G. Galudra, and U. Pradhan, 2010: *Opportunities for Reducing Emissions from all Land Uses in Indonesia: Policy Analysis and Case Studies.* ASB Partnership for the Tropical Forest Margins, World Agroforestry Centre (ICRAF), Nairobi, Kenya, 85 pp.

Van Oel, P.R., M.S. Krol, A.Y. Hoekstra, and R.R. Taddei, 2010: 2010: Feedback mechanisms between water availability and water use in a semi-arid river basin: a spatially explicit multi-agent simulation approach. *Environmental Modelling & Software*, **25(4)**, 433-443.

Varangis, P., P. Siegel, D. Giovannucci, and B. Lewin, 2003: *Dealing with the Coffee Crisis in Central America: Impacts and Strategies.* Policy Research Working Paper 2993, The World Bank, Development Research Group, Rural Development, The World Bank, Washington, DC, USA, 76 pp.

Verburg, R., E. Stehfest, G. Woltjer, and B. Eickhout, 2009: The effect of agricultural trade liberalisation on land-use related greenhouse gas. *Global Environmental Change*, **19(4)**, 434-446.

Vermeylen, S., 2010: Resource rights and the evolution of renewable energy technologies. *Renewable Energy*, **35(11)**, 2399-2405.

Verner, D., 2012: *Adaptation to a Changing Climate in the Arab Countries: A Case for Adaptation Governance and Leadership in Building Climate Resilience.* Mena Development Report, The World Bank, Washington, DC, USA, 402 pp.

Vincent, K., T. Cull, and E. Archer, 2010: Gendered vulnerability to climate change in Limpopo province, South Africa. In: *Gender and Climate Change: An Introduction* [Dankelman, I. (ed.)]. Earthscan, London,UK, pp. 160-167.

Vincent, K., T. Cull, D. Chanika, P. Hamazakaza, A. Joubert, E. Macome, and C. Mutonhodza-Davies, 2013: Farmers' responses to climate variability and change in southern Africa: is it coping or adaptation. *Climate and Development*, **5(3)**, 194-205.

Vogel, C. and K. O'Brien, 2006: Who can eat information? Examining the effectiveness of seasonal climate forecasts and regional climate-risk management strategies. *Climate Research*, **33**, 111-122.

Vohland, K. and B. Barry, 2009: A review of *in situ* rainwater harvesting (RWH) practices modifying landscape functions in African drylands. *Agriculture*, *Ecosystems and Environment*, **131(3-4)**, 119-127.

Walter, L.C., H.T. Rosa, and N.A. Streck, 2010: Simulação do rendimento de grãos de arroz irrigado 1 em cenários de mudanças climáticas (simulating grain yield of irrigated rice in climate change scenarios). *Pesquisa 3 Agropecuaria Brasileira*, **45(11)**, 1237-1245.

Walton, A., 2010: *Provincial-Level Projection of the Current Mountain Pine Beetle Outbreak: Update of the Infestation Projection Based on the 2009 Provincial Aerial Overview of Forest Health and the BCMPB Model (Year7)*. British Columbia Ministry of Forests and Range, Research and Knowledge Management Branch, Victoria, BC, Canada, 15 pp.

Wang, R., Z. Qiang, L. Hongyi, Y. Qiguo, Z. Hong, and W. Zhenguo, 2007: Impact of climate warming on cotton growth in the Hexi Corridor Area. *Advances in Climate Change Research*, **3(Suppl. 1)**, 57-59.

Wang, X. and Q. Zhang, 2012: Climate variability, change of land use and vulnerability in pastoral society: a case from Inner Mongolia. *Nomadic Peoples*, **16(1)**, 68-87.

Watkiss, P., 2011: Aggregate economic measures of climate change damages: explaining the differences and implications. *Wiley Interdisciplinary Reviews: Climate Change*, **2(3)**, 356-372.

Watkiss, P., T.E. Downing, and J. Dyszynski, 2010: *ADAPTCost Project: Analysis of the Economic Costs of Climate Change Adaptation in Africa.* United Nations Environment Programme (UNEP), Nairobi, Kenya, 35 pp.

Webster, D., 2002: *On the Edge: Shaping the Future of Peri-urban East Asia.* Asia/Pacific Research Center, Stanford, University, Stanford, CA, USA, 49 pp.

Weisbach, D. and C. Sunstein, 2008: *Climate Change and Discounting the Future: A Guide for the Perplexed*. Reg-Markets Center Working Paper No. 08-19, Harvard Public Law Working Paper No. 08-20, Harvard Law School Program on Risk Regulation Research Paper No. 08-12, doi:10.2139/ssrn.1223448.

Wellard, K., D. Kambewa, and S. Snapp, 2012: Farmers on the frontline: adaptation and change in Malawi. In: *Climate Change and Threatened Communities: Vulnerability, Capacity and Action* [A.P. Castro, D. Taylor, and D.W. Brokensha (ed.)]. Practical Action Publications, Rugby, UK, pp.41-56 .

Wertz-Kanounnikoff, S., B. Locatelli, S. Wunder, and M. Brockhaus, 2011: Ecosystem-based adaptation to climate change: what scope for payments for environmental services? *Climate and Development*, **3(2)**, 143-158.

Westerhoff, L. and B. Smit, 2009: The rains are disappointing us: dynamic vulnerability and adaptation to multiple stressors in the Afram Plains, Ghana. *Mitigation and Adaptation Strategies for Global Change*, **14(4)**, 317-337.

Westhoek, H., M. van den Berg, and J. Bakkes, 2006: Scenario development to explore the future of Europe's rural areas. *Agriculture Ecosystems & Environment*, **114(1)**, 7-20.

Wijeratne, M.A., A. Anandacoomaraswamy, M.K.S.L.D. Amarathunga, J. Ratnasiri, B.R.S.B. Basnayake, and N. Kalra, 2007: Assessment of impact of climate change on productivity of tea (*Camellia sinensis* L.) plantations in Sri Lanka. *Journal of the National Science Foundation of Sri Lanka*, **35(2)**, 119-126.

Wilbanks T.J., P. Romero Lankao, M. Bao, F. Berkhout, S. Cairncross, J.-P. Ceron, M. Kapshe, R. Muir-Wood, and R. Zapata-Marti, 2007: Industry, settlement and society. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 357-390.

Wittrock, V., S.N. Kulreshtha, and E. Wheaton, 2011: Canadian prairie rural communities: their vulnerabilities and adaptive capacities to drought. *Mitigation and Adaptation Strategies for Global Change*, **16(3)**, 267-290.

Wolfsegger, C., S. Gossling, and D. Scott, 2008: Climate change risk appraisal in the Austrian ski industry. *Tourism Review International*, **12(1)**, 13-23.

Womach, J., 2005: *Agriculture: Terms, Programs, and Laws.* Nova Science Publishers, New York, NY, USA, 234 pp.

World Bank, 2003: *Nicaragua Poverty Assessment.* Report No. 26128-NI, Central America Department, Latin America and the Caribbean Region, World Bank, Washington, DC, USA, 51 pp.

World Bank, 2007: *World Development Report 2008. Agriculture for Development.* The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 365 pp.

World Bank, 2008: *World Development Report 2009: Reshaping Economic Geography.* The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 383 pp.

World Bank, 2010a: *Economics of Adaptation to Climate Change: Synthesis Report.* The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 101 pp.

World Bank, 2010b: *Rising Global Interest in Farmland. Can It Yield Sustainable and Equitable Benefits*? The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 214 pp.

Wolsink, M., 2007: Planning of renewables schemes: deliberative and fair decision-making on landscape issues instead of reproachful accusations of non-cooperation. *Energy Policy*, **35(5)**, 2692-2704.

Wright, B.D., 2011: The economics of grain price volatility. *Applied Economic Perspectives and Policy*, **33(1)**, 32-58.

WTO, 2009: *International Trade Statistics 2009*. World Trade Organization (WTO), WTO, Geneva, Switzerland, 243 pp.

WTO, 2013: *International Trade Statistics 2012*. World Trade Organization (WTO), WTO, Geneva, Switzerland, 267 pp.

Würtenberger, L., T. Koellner, and C.R. Binder, 2006: Virtual land use and agricultural trade: estimating environmental and socio-economic impacts. *Ecological Economics*, **57(4)**, 679-697.

Wutich, A., A.B. York, A. Brewis, R. Stotts, and C.M. Roberts, 2012: Shared cultural norms for justice in water institutions: results from Fiji, Ecuador, Paraguay, New Zealand, and the U.S. *Journal of Environmental Managment*, **113**, 370-367.

Xu, J., Y. Yang, Z. Li, N. Tashi, R. Sharma, and J. Fang, 2008: Understanding land use, livelihoods, and health transitions among Tibetan nomads: a case from Gangga Township, Dingri County, TAR of China. *Ecohealth*, **5(2)**, 104-114.

Zagonari, F., 2010: Sustainable, just, equal, and optimal groundwater management strategies to cope with climate change: insights from Brazil. *Water Resources Management*, **24(12)**, 3731-3756.

Zhai, F. and J. Zhuang, 2009: *Agricultural Impact of Climate Change: A General Equilibrium Analysis with Special Reference to Southeast Asia.* ADBI Working Paper 131, Asian Development Bank Institute, Tokyo, Japan, 17 pp., www.adbi.org/files/2009.02.23.wp131.agricultural.impact.climate.change.pdf.

Zhao, L., Q.B. Wu, S.S. Marchenko, and N. Sharkhuu, 2010: Thermal state of permafrost and active layer in Central Asia during the International Polar Year. *Permafrost and Periglacial Processes*, **21(2)**, 198-207.

Ziervogel, G., 2004: Targeting seasonal climate forecasts for integration into household level decisions: the case of smallholder farmers in Lesotho. *The Geographical Journal*, **170(1)**, 6-21.

Ziervogel, G. and T.E. Downing, 2004: Stakeholder networks: improving seasonal climate forecasts. *Climatic Change*, **65(1-2)**, 73-101.

Ziervogel, G. and A. Taylor, 2008: Feeling stressed: integrating climate adaptation with other priorities in South Africa. *Environment*, **50(2)**, 32-41.

Ziervogel, G. and F. Zermoglio, 2009: Climate change scenarios and the development of adaptation strategies in Africa: challenges and opportunities. *Climate Research*, **40(2-3)**, 133-146.

Ziervogel, G., P. Johnston, M. Matthew, and P. Mukheibir, 2010a: Using climate information for supporting climate change adaptation in water resource management in South Africa. *Climatic Change*, **103(3-4)**, 537-554.

Ziervogel, G., A. Opere, I. Chagonda, J. Churi, A. Dieye, B. Houenou, S. Hounkponou, E. Kisiangani, E. Kituyi, C. Lukorito, A. Macharia, H. Mahoo, A. Majule, P. Mapfumo, F. Mtambanengwe, F. Mugabe, L. Ogallo, G. Ouma, A. Sall, and G. Wanda, 2010b: *Integrating Meteorological and Indigenous Knowledge-Based Seasonal Climate Forecasts for the Agricultural Sector. Lessons from Participatory Action Research in sub-Saharan Africa*. International Development Research Centre and the UK Department for International Development, IDRC, Ottawa, ON, Canada, 24 pp.

Zografos, C. and R.B. Howarth, 2010: Deliberative ecological economics for sustainability governance. *Sustainability*, **2(11)**, 3388-3417.

10 Key Economic Sectors and Services

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This chapter should be cited as:
Arent, D.J., R.S.J. Tol, E. Faust, J.P. Hella, S. Kumar, K.M. Strzepek, F.L. Tóth, and D. Yan, 2014: Key economic sectors and services. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659-708.

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Executive Summary

This chapter assesses the implications of climate change on economic activity in key economic sectors and services, on economic welfare, and on economic development.

For most economic sectors, the impact of climate change will be small relative to the impacts of other drivers (*medium evidence*, *high agreement*). Changes in population, age, income, technology, relative prices, lifestyle, regulation, governance, and many other aspects of socioeconomic development will have an impact on the supply and demand of economic goods and services that is large relative to the impact of climate change. {10.10}

Climate change will reduce energy demand for heating and increase energy demand for cooling in the residential and commercial sectors (*robust evidence*, *high agreement*); the balance of the two depends on the geographic, socioeconomic, and technological conditions. Increasing income will allow people to regulate indoor temperatures to a comfort level that leads to fast growing energy demand for air conditioning even in the absence of climate change in warm regions with low income levels at present. Energy demand will be influenced by changes in demographics (upward by increasing population and decreasing average household size), lifestyles (upward by larger floor area of dwellings), the design and heat insulation properties of the housing stock, the energy efficiency of heating/cooling devices, and the abundance and energy efficiency of other electric household appliances. The relative importance of these drivers varies across regions and will change over time. {10.2}

Climate change will affect different energy sources and technologies differently, depending on the resources (water flow, wind, insolation), the technological processes (cooling), or the locations (coastal regions, floodplains) involved (*robust evidence*, *high agreement*). Gradual changes in various climate attributes (temperature, precipitation, windiness, cloudiness, etc.) and possible changes in the frequency and intensity of extreme weather events will progressively affect operation over time. Climate-induced changes in the availability and temperature of water for cooling are the main concern for thermal and nuclear power plants. Several options are available to cope with reduced water availability but at higher cost; however, decreased efficiency of thermal conversion remains a primary concern. Similarly, already available or newly developed technological solutions allow firms to reduce the vulnerability of new structures and enhance the climate suitability of existing energy installations. {10.2}

Climate change may influence the integrity and reliability of pipelines and electricity grids (*medium evidence*, *medium agreement*). Pipelines and electric transmission lines have been designed and operated for more than a century in diverse and often extreme climatic conditions on land from hot deserts to permafrost areas and increasingly at sea. Owing to the private nature and high economic value to the energy sector, they have been designed to higher tolerance levels than most transportation infrastructure. Climate change may require changes in design standards for the construction and operation of pipelines and power transmission and distribution lines. Adopting existing technology from other geographical and climatic conditions may reduce the cost of adapting new infrastructure as well as the cost of retrofitting existing pipelines and grids to the changing climate, sea level, and weather conditions, which is likely to become more intense over time. {10.2}

Climate change will have impacts, positive and negative and varying in scale and intensity, on water supply infrastructure and water demand (*robust evidence*, *high agreement*), but the economic implications are not well understood. Economic impacts include flooding, scarcity, and cross-sectoral competition. Flooding can have major economic costs, both in term of impacts (capital destruction, disruption) and adaptation (construction, defensive investment). Water scarcity and competition for water—driven by institutional, economic, or social factors—may mean that water is not available in sufficient quantity or quality for some uses or locations. {10.3}

Climate change may negatively affect transport infrastructure (*limited evidence*, *high agreement*). Transport infrastructure malfunctions if the weather is outside the design range, which would happen more frequently as the climate continues to change. All infrastructure is vulnerable to freeze-thaw cycles. Paved roads are particularly vulnerable to temperature extremes, and unpaved roads and bridges to precipitation extremes. Transport infrastructure on ice or permafrost is especially vulnerable. {10.4}

Climate change will affect tourism resorts, particularly ski resorts, beach resorts, and nature resorts (*robust evidence*, *high agreement*) and tourists may spend their holidays at higher altitudes and latitudes (*medium evidence*, *high agreement*). The economic implications of climate change-induced changes in tourism demand and supply entail gains for countries closer to the poles and higher up the mountains and losses for other countries. The demand for outdoor recreation is affected by weather and climate, and impacts will vary geographically and seasonally. {10.6}

Climate change will affect insurance systems (*robust evidence*, *high agreement*). More frequent and/or intensive weather disasters as projected for some regions/hazards will increase losses and loss variability in various regions and challenge insurance systems to offer affordable coverage while raising more risk-based capital, particularly in low- and middle-income countries. Economic-vulnerability reduction through insurance has proven effective. Large-scale public-private risk prevention initiatives and government insurance of the non-diversifiable portion of risk offer example mechanisms for adaptation. Commercial reinsurance and risk-linked securitization markets also have a role in ensuring financially resilient insurance and risk transfer systems. {10.7}

Climate change will affect the health sector (*medium evidence*, *high agreement*) through increases in the frequency, intensity, and extent of extreme weather events as well as increasing demands for health care services and facilities, including public health programs, disease prevention activities, health care personnel, infrastructure, and supplies related to treatment of infectious diseases and temperature-related events. {10.8}

Well-functioning markets provide an additional mechanism for adaptation and thus tend to reduce negative impacts and increase positive ones for any specific sector or country (*medium evidence*, *high agreement*). The impacts of climate on one sector of the economy of one country in turn affect other sectors and other countries though product and input markets. Markets increase overall welfare, but not necessarily welfare in every sector and country. {10.9}

The impacts of climate change may decrease productivity and economic growth, but the magnitude of this effect is not well understood (*limited evidence*, *high agreement*). Climate could be one of the causes why some countries are trapped in poverty, and climate change may make it harder to escape poverty. {10.9}

Global economic impacts from climate change are difficult to estimate. Economic impact estimates completed over the past 20 years vary in their coverage of subsets of economic sectors and depend on a large number of assumptions, many of which are disputable, and many estimates do not account for catastrophic changes, tipping points, and many other factors. With these recognized limitations, the incomplete estimates of global annual economic losses for additional temperature increases of ~2°C are between 0.2 and 2.0% of income (±1 standard deviation around the mean) (*medium evidence*, *medium agreement*). Losses are *more likely than not* to be greater, rather than smaller, than this range (*limited evidence*, *high agreement*). Additionally, there are large differences between and within countries. Losses accelerate with greater warming (*limited evidence*, *high agreement*), but few quantitative estimates have been completed for additional warming around 3°C or above. Estimates of the incremental economic impact of emitting carbon dioxide lie between a few dollars and several hundreds of dollars per tonne of carbon (*robust evidence*, *medium agreement*). Estimates vary strongly with the assumed damage function and discount rate. {10.9}

Not all key economic sectors and services have been subject to detailed research. Few studies have evaluated the possible impacts of climate change on mining, manufacturing, or services (apart from health, insurance, and tourism). Further research, collection, and access to more detailed economic data and the advancement of analytic methods and tools will be required to assess further the potential impacts of climate on key economic systems and sectors. {10.5, 10.8, 10.10}

10.1. Introduction and Context

This chapter discusses the implications of climate change on key economic sectors and services, for example, economic activity. Other chapters discuss impacts from a physical, chemical, biological, or social perspective. Economic impacts cannot be isolated; therefore, there are a large number of cross-references to sections in other chapters of this report. In some cases, particularly agriculture, the discussion of the economic impacts is integrated with the other impacts.

Focusing on the potential impact of climate change on economic activity, this chapter addresses questions such as: How does climate change affect the demand for a particular good or service? What is the impact on its supply? How do supply and demand interact in the market? What are the effects on producers and consumers? What is the effect on the overall economy, and on welfare?

An inclusive approach was taken, discussing all sectors of the economy. Section SM10.1 found in this chapter's on-line supplementary material shows the list of sectors according to the International Standard Industrial Classification. This assessment reflects the breadth and depth of the state of knowledge across these sectors; many of which have not been evaluated in the literature. We extensively discuss five sectors: energy (Section 10.2), water (Section 10.3), transport (Section 10.4), tourism (Section 10.6), and insurance (Section 10.7). Other primary and secondary sectors are discussed in Section 10.5, and Section 10.8 is devoted to other service sectors. Food and agriculture is addressed in Chapter 7. Sections 10.2 through 10.8 discuss individual sectors in isolation. Markets are connected, however. Section 10.9 therefore assesses the implications of changes in any one sector on the rest of the economy. It also discusses the effect of the impacts of climate change on economic growth and development. Chapter 19 assesses the impact of climate change on economic welfare—that is, the sum of changes in consumer and producer surplus, including for goods and services not traded within the formal economy. This is not attempted here. The focus is on economic activity. Section 10.10 discusses whether there may be vulnerable sectors that have yet to be studied.

Previous assessment reports by the IPCC did not have a chapter on "key economic sectors and services." Instead, the material assembled here was spread over a number of chapters. The Fourth Assessment Report (AR4) is referred to in the context of the sections below. In some cases, however, the literature is so new that previous IPCC reports did not discuss these impacts at any length.

10.2. Energy

Studies conducted since AR4 and assessed here confirm the main insights about the impacts of climate change on energy demand as reported in the Second Assessment Report (SAR; Acosta et al., 1995) and reinforced by the Third Assessment Report (TAR; Scott et al., 2001) and AR4 (Wilbanks et al., 2007): ceteris paribus, in a warming world, energy demand for heating will decline and energy demand for cooling will increase; the balance of the two depends on the geographic, socioeconomic, and technological conditions. The relative importance of temperature changes among the drivers of energy demand varies across regions and will change over time. Earlier IPCC assessments did not write much about energy supply, but an increasing number of studies now explore its vulnerability, impacts, and adaptation options (Karl et al., 2009; Troccoli, 2010; Ebinger and Vergara, 2011). The energy sector will be transformed by climate policy (WGIII AR5 Chapter 7) but impacts of climate changes too will be important for secure and reliable energy supply.

10.2.1. Energy Demand

Most studies conducted since AR4 explore the impacts of climate change on residential energy demand, particularly electricity (Mideksa and Kallbekken, 2010). Some studies encompass the commercial sector as well but very few deal with industry and agriculture. In addition to a few global studies based on global energy or integrated assessment models, the new studies tend to focus on specific countries or regions (Zachariadis, 2010; Olonscheck et al., 2011), rely on improved methods (more advanced statistical techniques; de Cian et al., 2013) and data (both

Frequently Asked Questions

FAQ 10.1 | Why are key economic sectors vulnerable to climate change?

Many key economic sectors are affected by long-term changes in temperature, precipitation, sea level rise, and extreme events, all of which are impacts of climate change. For example, energy is used to keep buildings warm in winter and cool in summer. Changes in temperature would thus affect energy demand. Climate change also affects energy supply through the cooling of thermal plants, through wind, solar, and water resources for power, and through transport and transmission infrastructure. Water demand increases with temperature but falls with rising carbon dioxide (CO_2) concentrations as CO_2 fertilization improves the water use efficiency plant respiration. Water supply depends on precipitation patterns and temperature, and water infrastructure is vulnerable to extreme weather, while transport infrastructure is designed to withstand a particular range of weather conditions, and climate change would expose this infrastructure to weather outside historical design criteria. Recreation and tourism are weather-dependent. As holidays are typically planned in advance, tourism depends on the *expected* weather and will thus be affected by climate change. Health care systems are also impacted, as climate change affects a number of diseases and thus the demand for and supply of health care.

historical and regional climate projections), and many of them explicitly include non-climatic drivers of energy demand (e.g., sources). A few studies consider changes in demand together with changes in climate-dependent energy sources, such as hydropower (Hamlet et al., 2010).

Sorting the assessed studies according to the present climate (represented by mean annual temperature based on 1971–2000 climatology) and current income (represented by gross domestic product (GDP) per capita in 2009), the general patterns are as follows. In countries and regions with already high incomes, climate-related changes in energy demand will be driven primarily by increasing temperatures. In countries/regions with high incomes and warm climates, increasing temperatures will be associated with heavier use of air conditioning. In countries/regions with high incomes and temperate and cold climates, increasing temperatures will result in lower demands for various energy forms (electricity, gas, coal, oil). Increasing incomes will play a marginal role in these countries and regions. In contrast, changes in income will be the main driver of increasing demand for energy (mainly electricity for air conditioning and transportation fuels) in present-day low-income countries in warm climates. Neither indicator is ideal because country-level mean annual temperatures for large countries can hide large regional differences and average incomes may conceal large disparities, but they help cluster the national and regional studies in the search for general finding.

At the global scale, energy demand for residential air conditioning in summer is projected to increase rapidly in the 21st century under the reference climate change scenario (medium population and economic growth globally, but faster economic growth in developing countries; no mitigation policies in addition to those in place in 2008) by the Targets IMAGE Energy Regional Model/Integrated Model to Assess the Global Environment (TIMER/IMAGE) model (Isaac and Van Vuuren, 2009). The increase is from nearly 300 TWh in 2000 to about 4000 TWh in 2050 and more than 10,000 TWh in 2100, about 75% of which is due to increasing income in emerging market countries and 25% is due to climate change. Energy demand for heating in winter increases too, but much less rapidly, since in most regions with the highest need for heating, incomes are already high enough for people to heat their homes to the desired comfort level (except in some poor households). In these regions, energy demand for heating will decrease.

These general patterns and especially the quantitative results of the projected shifts in energy and electricity demand can be modified by many other factors. In addition to changes in temperatures and incomes, the actual energy demand will be influenced by changes in demographics (upward by increasing population and decreasing average household size, mixed effects from urbanization), lifestyles (upward by larger floor area of dwellings), building codes and regulations for the design and insulation of the housing stock, the energy efficiency of heating/cooling devices, the abundance and energy efficiency of other electric household appliances, the price of energy, and so forth.

10.2.2. Energy Supply

Changes in climate attributes (temperature, precipitation, windiness, cloudiness, etc.) will affect different energy sources and technologies differently. Gradual climate change will progressively affect the operation of energy installations and infrastructure over time. Possible changes in the frequency and intensity of extreme weather events (EWEs) as a result of climate change represent a different kind of hazard for them. (EWEs are weather events that are rare at a particular place and time of the year; they are usually defined as rare or rarer than the 10th and 90th percentiles of a probability density function estimated from observations; see Glossary). Rummukainen (2013) and Mika (2013) summarize recent trends and prospects relevant for the energy sector. This section assesses the most important impacts and adaptation options in both categories. Table 10-1 provides an overview.

Currently, thermal power plants provide about 80% of global electricity and their share is projected to remain high in most mitigation scenarios (IEA, 2010a). Thermal power plants can be designed to operate under diverse climatic conditions, from the cold Arctic to the hot tropical regions and are normally well adapted to the prevailing conditions. However, they might face new challenges and will need to respond by hard (design or structural methods) or soft (operating procedures) measures as a result of climate change.

A general impact of climate change on thermal power generation (including combined heat and power) is the decreasing efficiency of thermal conversion as a result of rising temperature that cannot be offset per se. Yet there is much room to improve the efficiency of currently operating subcritical steam power plants (IEA, 2010b). As new materials allow higher operating temperatures in coal-fired power plants (Gibbons, 2012), supercritical and ultra-supercritical steam-cycle plants (operating at much higher pressure and temperature conditions than conventional power plants) will reach even higher efficiency that can more than compensate the efficiency losses due to higher temperatures. Yet in the absence of climate change, these efficiency gains from improved technology would reduce the costs of energy, so there is still a net economic loss due to climate change. Another problem facing thermal power generation in many regions is the decreasing volume and increasing temperature of water for cooling, leading to reduced power generation, operation at reduced capacity, and even temporary shutdown of power plants (Ott and Richter, 2008; Hoffmann et al., 2010; IEA, 2012; Sieber, 2013). Both problems will be exacerbated if carbon dioxide (CO_2) capture and handling equipment is added to fossil-fired power plants: energy efficiency declines by 8 to 14% (IPCC, 2005) and water requirement per MWh electricity generated can double (Macknick et al., 2011). Using partial equilibrium river basin models, (Hurd et al., 2004; Strzepek et al., 2013) estimate USA welfare loses due to thermal cooling water changes at US$622 million per year up to 2100, a 6.5% welfare loss in the energy sector. Van Vliet et al. (2012) find that the southeastern United States, Europe, eastern China, southern Africa, and southern Australia could potentially be affected by reduced water available for thermoelectric power and drinking water, inducing changes to dry or hybrid cooling (with concomitant loss in electric output), or plant shut downs, with associated impacts on local and regional economic activity.

Adaptation possibilities range from relatively simple and low-cost options such as exploiting non-traditional water sources and re-using process water to measures such as installing dry cooling towers, heat pipe exchangers, and regenerative cooling (Ott and Richter, 2008; De Bruin et al., 2009), all which increase costs. Water use regulation, heat

Table 10-1 | Main projected impacts of climate change and extreme weather events on energy supply and the related adaptation options.

Technology	Changes in climatic or related attributes	Possible impacts	Adaptation options
Thermal and nuclear power plants	Increasing air temperature	Reduces efficiency of thermal conversion by 0.1–0.2% in the USA; by 0.1–0.5% in Europe, where the capacity loss is estimated in the range of 1–2% per 1°C temperature increase, accounting for decreasing cooling efficiency and reduced operation level/shutdown	Siting at locations with cooler local climates where possible
	Changing (lower) precipitation and increasing air temperature increases temperature and reduces the availability of water for cooling.	Less power generation; annual average load reduction by 0.1–5.6% depending on scenario	Use of non-traditional water sources (e.g., water from oil and gas fields, coal mines and treatment, treated sewage); re-use of process water from flue gases (can cover 25–37% of the power plant's cooling needs), coal drying, condensers (drier coal has higher heating value, cooler water enters cooling tower), flue-gas desulfurization; using ice to cool air before entering the gas turbine increases efficiency and output, melted ice used in cooling tower; condenser mounted at the outlet of cooling tower to reduce evaporation losses (by up to 20%). Alternative cooling technologies: dry cooling towers, regenerative cooling, heat pipe exchangers; costs of retrofitting cooling options depend on features of existing systems, distance to water, required additional equipment, estimated at US$250,000–500,000 per megawatt
	Increasing frequency of extreme hot temperatures	Exacerbating impacts of warmer conditions: reduced thermal and cooling efficiency; limited cooling water discharge; overheating buildings; self-ignition of coal stockpiles	Cooling of buildings (air conditioning) and of coal stockpiles (water spraying)
	Drought: reduced water availability	Exacerbating impacts of warmer conditions, reduced operation and output, shutdown	Same as reduced water availability under gradual climate change
Hydropower	Increase/decrease in average water availability	Increased/reduced power output	Schedule release to optimize income
	Changes in seasonal and inter-annual variation in inflows (water availability)	Shifts in seasonal and annual power output; floods and lost output in the case of higher peak flows	Soft: adjust water management Hard: build additional storage capacity, improve turbine runner capacity
	Extreme precipitation causing floods	Direct and indirect (by debris carried from flooded areas) damage to dams and turbines, lost output due to releasing water through bypass channels	Soft: adjust water management Debris removal Hard: increase storage capacity
Solar energy	Increasing mean temperature	Improving performance of TH (especially in colder regions), reducing efficiency of PV and CSP with water cooling; PV efficiency drops by ~0.5% per 1°C temperature increase for crystalline silicon and thin-film modules as well, but performance varies across types of modules, with thin film modules performing better; long-term exposure to heat causes faster aging.	
	Changing cloudiness	Increasing unfavorable (reduced output), decreasing beneficial (increased output) for all types, but evacuated tube collectors for TH can use diffuse insolation. CSP more vulnerable (cannot use diffuse light)	Apply rougher surface for PV panels that use diffuse light better; optimize fixed mounting angle for using diffuse light, apply tracking system to adjust angle for diffuse light conditions; install/increase storage capacity
	Hot spells	Material damage for PV, reduced output for PV and CSP; CSP efficiency decreases by 3–9% as ambient temperature increases from 30 to 50°C and drops by 6% (tower) to 18% (trough) during the hottest 1% of time	Cooling PV panels passively by natural air flows or actively by forced air or liquid coolants
	Hail	Material damage to TH: evacuated tube collectors are more vulnerable than flat plate collectors. Fracturing as glass plate cover, damage to photoactive material	Flat plate collectors: using reinforced glass to withstand hailstones of 35 mm (all of 15 tested) or even 45 mm (10 of 15 tested); only 1 in 26 evacuated tube collectors withstood 45-mm hailstones. Increase protection to current standards or beyond them
Wind power	Windiness: total wind resource (multi-year annual mean wind power densities); likely to remain within ±50% of current values in Europe and North America; within ±25% of 1979–2000 historical values in contiguous USA	Change in wind power potential	Site selection
	Wind speed extremes: gust, direction change, shear	Structural integrity from high structural loads; fatigue, damage to turbine components; reduced output	Turbine design, lidar-based protection

Notes: CSP = concentrating solar power; PV = photovoltaic; TH = thermal heating.

Sources: EPA (2001); Parkpoom et al. (2005); Norton (2006); Pryor et al. (2006); Walter et al. (2006); Christensen and Busuioc (2007); DOE (2007); NETL National Energy Technology Laboratory (2007); Schaefli et al. (2007); Bloom et al. (2008); Feeley III et al. (2008); Haugen and Iversen (2008); Leckebusch et al. (2008); Markoff and Cullen (2008); Ott and Richter (2008); Sailor et al. (2008); Droogers (2009); Förster and Lilliestam (2009); Honeyborne (2009); Kurtz et al. (2009); SPF (2009); Hoffmann et al. (2010); Pryor and Barthelmie (2010, 2011, 2013); Pryor and Schoof (2010); Kurtz et al. (2011); Linnerud et al. (2011); Mukheibir (2013); Patt et al. (2013); Sieber (2013); Williams (2013).

discharge restrictions, and occasional exemptions might be an institutional adaptation (Eisenack and Stecker, 2012). Though it is easier to plan for changing climatic conditions and select the site and the conforming cost-efficient cooling technology for new builds, response options are more limited for existing power plants, especially for those toward the end of their economic lifetime.

Climate change impacts on thermal efficiency and cooling water availability affect nuclear power plants as well but the safety regulations are stricter than for fossil-fired plants (Williams and Toth, 2013). A range of alternative cooling options are available to deal with water deficiency, ranging from re-using wastewater and recovering evaporated water (Feeley III et al., 2008) to installing dry cooling (EPA, 2001).

The implications of EWEs for nuclear plants can be severe if not properly addressed. Reliable interconnection (on-site power and instrumentation connections) of intact key components (reactor vessel, cooling equipment, control instruments, back-up generators) is indispensable for the safe operation and/or shutdown of a nuclear reactor. For most of the existing global nuclear fleet, a reliable connection to the grid for power to run cooling systems and control instruments in emergency situations is another crucial item (IAEA, 2011). Several EWEs can damage the components or disrupt their interconnections. Preventive and protective measures include technical and engineering solutions (circuit insulation, shielding, flood protection) and adjusting operation to extreme conditions (reduced capacity, shutdown) (Williams and Toth, 2013).

Hydropower is by far the largest of renewable energy sources in the current electricity mix. It is projected to remain important in the future, irrespective of the climate change mitigation targets in many countries (IEA, 2010a,b). The resource base of hydropower is the hydrologic cycle driven by prevailing climate and topology. The former makes the resource base and hence hydropower generation highly dependent on future changes in climate and related changes in extreme weather events (Ebinger and Vergara, 2011; Mukheibir, 2013).

Assessing the impacts of climate change on hydropower generation is highly complex. A series of nonlinear and region-specific changes in mean annual and seasonal precipitation and temperatures, the resulting evapotranspiration losses, shifts in the share of precipitation falling as snow and the timing of its release from high elevation, and the climate response of glaciers make resource estimates difficult (see Chapters 2 and 3) while regional changes in water demand due to changes in population and economic activities (especially irrigation demand for agriculture) present competition for water resources that are hard to project (see Section 10.3). Further complications stem from the possibly increasing need to combine hydropower generation with changing flood control and ecological (minimum dependable flow) objectives induced by changing climate regimes. For hydropower locations, adaption to climate change to maintain output has been reported; in Ethiopia, Block and Strzepek (2012) report that capital expenditures through 2050 may either decrease by approximately 3% under extreme wet scenarios or increase by up to 4% under a severe dry scenario. In the Zambezi river basin, hydropower may fall by 10% by 2030, and by 35% by 2050 under the driest scenario (Strzepek et al., 2012). Lower generation is likely in the upstream power stations of the Zambezi basin and increases are *likely* downstream (Fant et al., 2013).

Focusing on the possible impacts of climate change on hydroelectricity and the adaptation options in the sector in response to the changes in the amount, the seasonal and interannual variations of available water, and in other demands, the conclusion from the literature is that the overall impacts of climate change and EWEs on hydropower generation by 2050 is expected to be slightly positive in most regions (e.g., in Asia, by 0.27%) and negative in some (e.g., in Europe, by –0.16%), with diverging patterns across regions, watersheds within regions, and even river basins within watersheds (IPCC, 2011). Adaptation responses and planning tools for long-term hydrogeneration may need to be enhanced to cope with slow but persistent shifts in water availability. Short-term management models may need to be enhanced to deal with the impacts of EWEs. A series of hard (raising dam walls, adding bypass channels) and soft (adjusting water release) measures are available to protect the related infrastructure (dams, channels, turbines, etc.) and optimize incomes by timing generation when electricity prices are high (Mukheibir, 2013).

Solar energy is expected to increase from its currently small share in the global energy balance across a wide range of mitigation scenarios (IEA, 2008, 2009, 2010a,b). The three main types of technologies for harnessing energy from insolation include thermal heating (TH; by flat plate, evacuated tube, and unglazed collectors), photovoltaic (PV) cells (crystalline silicon and thin film technologies), and concentrating solar power (CSP; power tower and power trough producing heat to drive a steam turbine for generating electricity). The increasing body of literature exploring the vulnerability and adaptation options of solar technologies to climate change and EWEs is reviewed by Patt et al. (2013).

All types of solar energy are sensitive to changes in climatic attributes that directly or indirectly influence the amount of insolation reaching them. If cloudiness increases under climate change (WGI AR5 Chapters 11, 12), the intensity of solar radiation and hence the output of heat or electricity would be reduced. Efficiency losses in cloudy conditions are less for technologies that can operate with diffuse light (evacuated tube collectors for TH, PV collectors with rough surface). Since diffuse light cannot be concentrated, CSP output would cease under cloudy conditions but the easy and relatively inexpensive possibility to store heat reduces this vulnerability if sufficient volume of heat storage is installed (Khosla, 2008; Richter et al., 2009).

The exposure of sensitive material to harsh weather conditions is another source of vulnerability for all types of solar technologies. Windstorms can damage the mounting structures directly and the conversion units by flying debris, whereby technologies with smaller surface areas are less vulnerable. Hail can also cause material damage and thus reduced output and increased need for repair. Depending on regional conditions, strong wind can deposit sand and dust on the collector's surface, reducing efficiency and increasing the need for cleaning.

Climate change and EWE hazards per se do not pose any particular constraints for the future deployment of solar technologies. Technological development continues in all three solar technologies toward new designs, models, and materials. An objective of these development efforts is to make the next generation of solar technologies less vulnerable to existing physical challenges, changing climatic conditions, and the impacts of EWEs. Technological development also results in a diverse portfolio of models to choose from according to the climatic and

weather characteristics of the deployment site. These development efforts can be integrated in addressing the key challenge for solar technologies today: reducing the costs.

Harnessing wind energy for power generation is an important part of the climate change mitigation portfolio in many countries. Assessing the possible impacts of climate change and EWEs and identifying possible adaptation responses for wind energy is complicated by the complex dynamics characterizing this generation source. Relevant attributes of climate are expected to change; the technology is evolving (blade design, other components); see Kong et al. (2005) and Barlas and Van Kuik (2010); there is an increasing deployment offshore and a transition to larger turbines (Garvey, 2010) and to larger sites (multi megawatt arrays) (Barthelmie et al., 2008).

The key question concerning the impacts of a changing climate regime on wind power is related to the resource base: how climate change will rearrange the temporal (inter- and intra-annual variability) and spatial (geographical distribution) characteristics of the wind resource. In the next few decades, wind resources (measured in terms of multi-annual wind power densities) are estimated to remain within the ±50% of the mean values over the past 20 years in Europe and North America (Pryor and Barthelmie, 2010). The wide range of the estimates results from the circulation and flow regimes in different General Circulation Models (GCMs) and Regional Climate Models (RCMs) (Bengtsson et al., 2006; Pryor and Barthelmie, 2010). A set of four GCM-RCM combinations for the period 2041–2062 indicates that average annual mean energy density will be within ±25% of the 1979–2000 values in all 50-km grid cells over the contiguous USA (Pryor et al., 2011; Pryor and Barthelmie, 2013). Yet, little is known about changes in the interannual, seasonal, or diurnal variability of wind resources.

Wind turbines already operate in diverse climatic and weather conditions. As shown in Table 10-1, siting, design, and engineering solutions are available to cope with various impacts of gradual changes in relevant climate attributes over the coming decades. The requirements to withstand extreme loading conditions resulting from climate change are within the safety margins prescribed in the design standards, although load from combinations of extreme events may exceed the design thresholds (Pryor and Barthelmie, 2013). In summary, the wind energy sector does not face insurmountable challenges resulting from climate change.

In the coal fuel cycle, vulnerability in mining depends on mining method. Surface mining might be particularly affected by high precipitation extremes and related floods and erosion, and temperature extremes, especially extreme cold that might encumber extraction for some time, whereas impacts on coal cleaning and operation of underground mines will probably be less severe (Ekman, 2013). Changes in drainage and runoff regulation for on-site coal storage as well as in coal handling might be required due to the increased moisture content of coal and more energy might be required for coal drying before transportation (CCSP, 2007). At the back end of the fuel cycle, the management of fly-ash, bottom ash, and boiler slag may need to be modified in response to changes in some EWE patterns such as wind, precipitation, and floods. Impacts on biomass-based energy sources are discussed in Chapter 7 of this report.

Climate- and weather-related hazards in the oil and gas sector include tropical cyclones with potentially severe effects on offshore platforms and onshore infrastructure as well, leading to more frequent production interruptions and evacuation (Cruz and Krausmann, 2013). Gradual changes in air temperature and precipitation are projected to generate risk and opportunities for the oil and gas industry. For example, new areas for oil and gas exploration could open in the Arctic, potentially increasing the technically recoverable resource base (Cruz and Krausmann, 2013). Reduced sea ice thickness and coverage might open new shipping routes, thus reducing shipping costs, while ice scour and ice pack loading on marine structures would increase. However, most changes involve increased risks, such as thawing permafrost would increase construction costs on unstable ground relative to ice-based construction, while thaw subsidence would trigger increased maintenance costs. Sea level rise (SLR) and coastal erosion would degrade coastal barriers, damage facilities, and trigger relocation (Dell and Pasteris, 2010).

10.2.3. Transport and Transmission of Energy

Primary energy sources (coal, oil, gas, uranium), secondary energy forms (electricity, hydrogen, warm water), and waste products (CO_2, coal ash, radioactive waste) are transported in diverse ways to distances ranging from a few to thousands of kilometers. The transport of energy-related materials by ships (ocean and inland waters), rail, and road are exposed to the same impacts of climate change as the rest of the transport sector (see Section 10.4). This subsection deals only with transport modes that are unique to the energy sector (power grid) or predominantly used by it (pipelines). Table 10-2 provides an overview of the impacts of climate change and EWEs on energy transmission, together with the options to reduce vulnerability.

Pipelines play a central role in the energy sector by transporting oil and gas from the wells to processing and distributing centers to distances from a few hundred to thousands of kilometers. With the potential spread of CO_2 capture and storage (CCS) technology, another important function will be to deliver CO_2 from the capture site (typically fossil power plants) to the storage site onshore or offshore. Pipelines have been operated for over a century in diverse climatic conditions on land from hot deserts to permafrost areas and increasingly at sea. This implies that technological solutions are available for the construction and operation of pipelines under diverse geographical and climatic conditions. Yet adjustments may be needed in existing pipelines and improvements in the design and deployment of new ones in response to the changing climate and weather conditions.

In addition to reduced line-heating and dilution needs due to reduced viscosity of liquid fuels under warmer temperatures, pipelines will be affected mainly by secondary impacts of climate change: SLR in coastal regions, melting permafrost in cold regions, floods washing away infrastructure, landslides triggered by heavy rainfall, and bushfires caused by heat waves or extreme temperatures in hot regions. A proposed way to reduce vulnerability to these events is to amend land zoning codes, risk-based design, and construction standards for new pipelines, and structural upgrades to existing infrastructure (Antonioni et al., 2009; Cruz and Krausmann, 2013).

Table 10-2 | Main impacts of climate change and extreme weather events on pipelines and the electricity grid.

Technology	Changes in climatic or related attribute	Impacts	Adaptation options
Pipelines	Melting permafrost	Destabilizing pillars, obstructing access for maintenance and repair	Adjust design code and planning criteria, install disaster mitigation plans
	Increasing high wind, storms, hurricanes	Damage to offshore and onshore pipelines and related equipment, spills; lift and blow heavy objects against pipelines, damage equipment	Enhance design criteria, update disaster preparedness
	Flooding caused by heavy rain, storm surge, or sea level rise	Damage to pipelines, spills	Siting (exclude flood plains), waterproofing
Electricity grid	Increasing average temperature	Increased transmission line losses	Include increasing temperature in the design calculation for maximum temperature/rating
	Increasing high wind, storms, hurricanes	Direct mechanical damage to overhead lines, towers, poles, substations, flashover caused by live cables galloping and thus touching or getting too close to each other; indirect mechanical damage and short circuit by trees blown over or debris blown against overhead lines	Adjust wind loading standards, reroute lines alongside roads or across open fields; manage vegetation; improve storm and hurricane forecasting
	Extreme high temperatures	Lines and transformers may overheat and trip off; flashover to trees underneath expanding cable	Increase system capacity, increase tension in the line to reduce sag, add external coolers to transformers
	Combination of low temperature, wind and rain, ice storm	Physical damage (including collapse) of overhead lines and towers caused by ice build-up on them	Enhance design standard to withstand larger ice and wind loading, reroute lines alongside roads or across open fields; improve forecasting of ice storms impacts on overhead lines and on transmission circuits

Sources: Bayliss (1996); Krausmann and Mushtaq (2008); Reed (2008); Hines et al. (2009); Winkler et al. (2010); Vlasova and Rakitina (2010); McColl (2012); Cruz and Krausmann (2013); Ward (2013).

Owing to the very function of the electricity grid to transmit power from generation units to consumers, the bulk of its components (overhead lines, substations, transformers) are located outdoors and exposed to EWE. The power industry has developed numerous technical solutions and related standards to protect assets and provide reliable electricity supply under existing climate and weather conditions worldwide. However, these assets and the reliability of supply may be vulnerable to changes in the frequency and intensity of EWEs under changing climate conditions (DOE, 2013). Higher average temperatures increase transmission efficiency and reduce current carrying capacity, but this effect is relatively small compared to the physical and monetary damages that can be caused by EWEs (Ward, 2013). Historically, high wind conditions, including storms, hurricanes, and tornados, have been the most frequent cause of grid disruptions (mainly due to damages to the distribution networks); and more than half of the damage was caused by trees (Reed, 2008). Other impacts include freezing precipitation, ice and winter storms, wildfires caused by higher temperatures, less precipitation, and increased tree death caused by pests. If the frequency and power of high wind conditions, as well as extreme precipitation events, will increase in the future, vegetation management along existing power lines, and rerouting new transmission lines along roads or across open fields or moving them underground might help reduce related risks. An important institutional option is to redefine technical standards to provide incentives for grid operators to implement appropriate adaptation measures. Such measures are less expensive to implement as part of the maintenance-renewal cycle than as independent retrofit measures.

The economic importance of a reliable transmission and distribution network is highlighted by the fact that the damage to customers tends to be much higher than the price of electricity not delivered (lost production, electricity enabled commerce, service delivery, food spoilage, lost or restricted water availability). Losses can be minimized through efficient rationing of electricity (de Nooij et al., 2009) if generation is the limiting factor. Designing and building climate-resilient infrastructure will depend on technical standards, market governance, and the type and degree of liberalization and deregulation of grid services.

10.2.4. Macroeconomic Impacts

Most economic research related to climate change impacts on the energy sector has focused on mitigation rather than the economic implications of climate change itself. Table 10-3 summarizes the recent studies on the economic implications of climate change and extreme weather impacts in the energy sector.

Assessing across a broad array of studies that focus on different regions and regional divisions, examine different climate change impacts, include a different mix of sectors, model different time frames, make different assumptions about adaptation, and employ different types of models with different output metrics leads to the overall conclusion that the macroeconomic impact of climate change on energy demand is *likely* to be minimal in developed countries (Bosello et al., 2007a, 2009; Aaheim et al., 2009; Jochem et al., 2009; Eboli et al., 2010).

The current literature sheds less light on the implications for developing countries and on other climate impacts in the energy sector beyond those related to changes in energy demand. Europe is the focus of most of the literature so far. Only two studies focus on developing countries: Mexico and Brazil (Boyd and Ibarraran, 2009; de Lucena et al., 2010). Asia and Africa are not well represented, appearing as aggregated regions in only three global studies (Bosello et al., 2007a, 2009; Eboli et al., 2010). The limited results indicate that developing countries *likely* face a greater negative GDP impact with respect to climate change implications for the energy sector than developed countries, largely because of higher expected temperature changes (Aaheim et al., 2009; Boyd and Ibarraran, 2009; Eboli et al., 2010).

Table 10-3 | Economy-wide implications of impacts of climate change and extreme weather on the energy sector.

Study	Model type	Climate impacts modeled	Energy/economic impacts	Regions	Sectors studied
Bosello et al. (2009)	IAM	Rising temperatures/changing demand for energy; impacts from four other sectors/events (Global, 2001–2050)	Change in gross domestic product (GDP) in 2050 due to rising temperatures and changing energy demand: 0–0.75% (+1.2°C); –0.1% to 1.2% (+3.1°C)	14	4
Jorgenson et al. (2004)	CGE	Rising temperatures/changing demand for energy; climate impacts from three other sectors (USA, 2000–2100)	Optimistic adaptation: 4–6.7% higher energy productivity per year (2000–2100) Output from electricity: –6% in 2050; GDP is +0.7% (aggregate all sectors, average annual 2000–2100) Pessimistic adaptation: 0.5–2.2% lower energy productivity per year Output from electricity: +2% in 2050; GDP is –0.6% (aggregate impact all sectors)	1	35
Bosello et al. (2007a)	CGE	Rising temperatures/changing demand for energy (Global, 2050)	Change in GDP in 2050 (perfect competition): –0.297% to 0.027% Change in GDP in 2050 (imperfect competition): –0.303% to 0.027%	8	1
Aaheim et al. (2009)	CGE	Change in precipitation affects share of hydroelectric power; rising temperatures/changing demand for energy; impacts from four other sectors (Western Europe, 2071–2100)	Impact from all sectors in 2100: GDP in cooler regions: –1% to –0.25% GDP in warmer regions: –3% to –0.5% Adaptation can mitigate 80–85% of economic impact	8	11
Boyd and Ibarraran (2009)	CGE	Drought scenario affecting hydroelectric plus three other sectors (Mexico, 2005–2026)	• Generation output in 2026: –2.1% • Refining output: –10.1% • Coal output: –7.8% • NG output: –2% • Crude oil output: +1.7% • GDP: –3% With adaptation: • Generation output in 2026: 0.24% • Refining output: 1.36% • Coal output: 1.09% • NG output: 0.34% • Crude oil output: 0.22% • GDP: 0.33%	1	2
Jochem et al. (2009)	PE/CGE	Rising temperatures/changing demand for energy; change in technical potential of renewables; change in rainfall induces change in hydroelectric production; high temperatures induce water temperatures exceeding regulatory limits (Europe); high temperatures induce greater electric grid losses and lower thermal efficiency; generic extreme events induce reduced capital stock in CGE model (EU27+2, 2005–2050)	• GDP (Europe): –50 billion € p.a. in 2035 • GDP (Europe): –240 billion € p.a. in 2050 • GDP (EU regions): –0.1% to –0.4% in 2035 • GDP (EU regions): –0.6% to –1.3% in 2050 • Jobs (Europe): –380K in 2035 • Jobs (Europe): –1 million in 2050	25	1
Eboli et al. (2010a)	CGE	Rising temperatures/changing demand for energy; climate impacts in four other sectors modeled (Global, 2002–2100)	By 2100, change in GDP due to climate impacts on energy demand vary by country between about –0.15% and 0.7%. USA and Japan were negative and all other countries positive. Overall economic impact from all sectors is neutral to positive for developed countries and negative for developing ones.	8	17
Golombek et al. (2011)	PE	Rising temperatures/changing demand for energy; rising temperatures/reduced thermal efficiency; change in water inflow (Western Europe, 2030)	Net impact on the price of electricity is a 1% increase. Generation decreases by 4%.	13	4
de Lucena et al. (2010)	PE	Changing precipitation induces change in hydroelectric production; rising temperatures induce lower NG thermal efficiency; rising temperatures induce change in demand for energy (Brazil, 2010–2035)	New generating capacity needed to produce additional 153–162 TWh per year. Capital investment of US$48–51 billion, which is equivalent to 10 years of capital expenditures in Brazil's long-term energy plan. US$6.9–7.2 billion in additional annual operating expenses for each year in which worst-case hydroelectric production occurs	1	11
Bye et al. (2008)	PE	Water shortages (Nordic countries, hypothetical 2-year period)	Water shortage scenarios can lead to a 100% increase in electricity prices at peak demand over a 2-year period. Higher prices lead to marginal reductions in demand (about 1–2.25%).	4	1
Koch et al. (2012)	PE	High temperatures induce water temperatures exceeding regulatory limits (Berlin, 2010–2050)	Thermal plant outages amounting to 60 million € for plants in Berlin through 2050	1	1
Gabrielsen et al. (2005)	Econometric	Rising temperatures/changing demand for energy; change in water inflow; change in wind speeds (Nordic countries, 2000–2040)	Net change in electricity supply in 2040: 1.8% Change in electricity demand: 1.4% Change in electricity price: –1.0%	4	1

Table 10-3 (continued)

Study	Model type	Climate impacts modeled	Energy/economic impacts	Regions	Sectors studied
UNDP (2011)	PE	Damage Case 1 (DC1): hotter in both winter and summer—decreased demand for heating and increased demand for cooling; Damage Case 2 (DC2): colder in both winter and summer—increased demand for heating and decreased demand for cooling; Damage Case 3 (DC3): colder in the winter and hotter in the summer—increased demand for heating and increased demand for cooling (Macedonia, 2009–2030)	Change in electricity demand in residential and commercial sectors: • DC1: 3.5% • DC2: 0.3% • DC3: 8% Change in electricity system cost: • DC1: 0.8% • DC2: 0.06% • DC3: 1.74%	9	5
DOE (2009)	PE	Drought scenario (Western Electric Coordinating Council, USA, 2010–2020)	In 2020, 3.7% reduction in coal generation; 43.4% increase in NG generation; 29.3% reduction in hydroelectric generation. Production cost increase of US$3.5 billion. Average monthly electricity prices up 8.1% (Nov) to 24.1% (July)	1	1

Note: The regions indicated in the Regions column vary in size and are model-specific. CGE = Computable General Equilibrium; PE = Partial Equilibrium; IAM = Integrated Assessment Model.

Despite the considerable number of potential climate change and extreme weather phenomena—higher mean temperatures, changes in rainfall patterns, changes in wind patterns, changes in cloud cover and average insolation, lightning, high winds, hail, sand storms and dust, extreme cold, extreme heat, floods, drought, fire, and SLR—and their potential impacts on electricity generation and transmission systems, fuel infrastructure and transport systems, and energy demand (Williams, 2013), the range of impacts modeled in the literature (Table 10-3) is quite limited. Most studies consider changing energy demand (specifically, changes in electricity and fuel consumption for space heating/cooling) resulting from rising temperatures as the only or primary climate change impact. These studies draw on recent literature refining the relationship between climate change and energy demand: the demand for natural gas and oil in residential and commercial sectors tends to decline with climate change because of less need for space heating, and demand for electricity tends to increase because of greater need for space cooling (Gabrielsen et al., 2005; Kirkinen et al., 2005; Mansur et al., 2005; Eskeland and Mideksa, 2010; Mideksa and Kallbekken, 2010; Rübbelke and Vögele, 2010).

Studies using a Computable General Equilibrium (CGE) model that consider only climate impacts in the energy sector find that the effect on GDP in 2050 is in the range of –0.3% to 0.03% (Bosello et al., 2007a) and –1.3% to –0.6% (Jochem et al., 2009). These findings are largely consistent despite the fact that Bosello et al. (2007a, 2009) are global studies that model only the change in demand due to rising temperatures, whereas Jochem et al. (2009) focus on the European Union (EU) and model the change in demand plus six other climate impacts.

Studies using CGE models that examine the aggregate changes in GDP brought on by climate impacts in energy and several other sectors have also primarily found similar shifts in GDP. Aaheim et al. (2009) conclude that in 2100 in cooler regions in the EU, GDP changes by –1% to –0.25% and in warmer regions changes by –3% to –0.5%. Boyd and Ibarraran (2009) project a –3% change in GDP in 2026 for Mexico, consistent with the warmer regions modeled by Aaheim et al. (2009). Roughly consistent with each other, Aaheim et al. (2009) and Eboli et al. (2010) find GDP impacts for the predominantly cooler regions of Japan, the EU, Eastern Europe and the Former Soviet Union (EEFSU), and Rest of Annex I as having a "significant positive impact," while the predominantly warmer regions of the USA, EEx (China/India, Middle East/Most of Africa/Mexico/parts of Latin America), and the Rest of the World have a "significantly negative impact." Jorgenson et al. (2004) find that overall GDP impacts are –0.6% to 0.7% in 2050 for the USA, which stands in contrast to Eboli et al. (2010) with a "significantly negative impact" in the USA.

Several CGE studies attempt to evaluate how adaptation changes in the energy sector impact GDP but do not examine specific adaptation options since CGE models lack the necessary technological detail. They make general assumptions about the effectiveness of adaptation policy in reducing climate impacts. Jorgenson et al. (2004) find that pessimistic assumptions about adaptation imply a 0.6% reduction in GDP in 2050 but optimistic assumptions lead to a 0.7% gain in GDP. Aaheim et al. (2009) conclude that adaptation can mitigate the costs of climate change by 80% to 85%, and Boyd and Ibarraran (2009) find that adaptation can shift a 3% GDP loss in 2026 in Mexico to a gain in GDP of 0.33%.

Partial equilibrium models, by their nature, do not have a full macroeconomic representation and therefore rarely report changes in GDP. Instead, these models focus on details in the energy sector, such as price and quantity effects for fuels and electricity (and the mix of generation). For example, Rübbelke and Vögele (2013) conclude that the short-term effects of climate-related problems affecting water cooling and hydropower production can have negative distributional effects. de Lucena et al. (2010) find that rising temperature and changing precipitation lead to the need for an additional 153 to 162 TWh per year by 2035 with a capital investment of US$48 to 51 billion.

Golombek et al. (2011) report a 1% increase in the price of electricity for Western Europe in 2030 stemming from rising temperatures that affect demand and thermal efficiency of supply, as well as water inflow. UNDP (2011) finds between a 0.06% and 1.74% increase in electricity system costs for Macedonia resulting from temperature changes. Gabrielsen et al. (2005) conclude that for Nordic countries in 2040, as a result of rising temperatures that affect demand, changes in water

inflow, and changes in wind speeds, the wholesale price of electricity will decline by 10%. Koch et al. (2012) conclude that thermal plant outages in Berlin resulting from heat wave-driven water temperatures that exceed regulatory limits can amount to a cumulative cost of about US$80 million over the period 2010 through 2050 for 2850 MW of capacity. Assuming an 80% capacity factor, the premium for high water temperatures in Berlin is US$0.1 per MWh. The magnitude of change in electricity price is small in each of the previously mentioned studies that evaluate gradual temperature increases.

In contrast, studies that consider shorter-term heat waves and water shortages find considerably higher price impacts. Bye et al. (2008) consider a hypothetical water shortage scenario—25% lower inflow over 2 years—in Nordic countries and conclude that the price of electricity can double over a 2-year period and then return to normal as water flow returns. McDermott and Nilsen (2013) find more generally that electricity prices in Germany increase by 1% for every degree that water temperatures rise above 25°C and by 1% for every 1% that river levels fall. DOE (2009) also finds that a drought scenario can lead to average monthly electricity prices that are 8.1% (November) to 24.1% (July) higher. Pechan and Eisenack (2013) find that an equivalent of the 2006 German heat wave can result in an increase in electricity prices of 11% or even 24% (affected plants running at minimum output) and 50% (affected plants at zero output).

10.2.5. Summary

The balance of evidence emerging from the literature assessed in this section suggests that climate change per se will likely increase the demand for energy in most regions of the world. At the same time, increasing temperature will decrease the thermal efficiency of fossil, nuclear, biomass, and solar power generation technologies (Mideksa and Kallbekken, 2010). However, gradual temperature-induced impacts on energy supply will probably make a relatively small contribution to the cost of energy and electricity. Acute heat waves and droughts can have a much greater, albeit short-term, impact on electricity prices. In addition, many other potential climate impacts on energy supply are possible but have not been fully studied, leading to cost estimates to date, based only on temperature change, that underestimate the full cost of climate change on energy supply. Preexisting subsidies may distort signals for adaptation. Climate change impacts on energy supply will be part of an evolving picture dominated by technological development in the pursuit for safer, less expensive, and more reliable energy sources and technologies as well as mitigation and adaptation response pathways.

Given the limitations in the literature, sweeping conclusions about results may be premature on macroeconomic implications. However, some narrow conclusions are possible. The change in GDP due to temperature-induced changes in energy demand—even if combined with other climate impacts—range from –3% to 1.2%. Jochem et al. (2009) provide the most detailed and comprehensive study, and report only a 1.3% drop in GDP in 2050 in Europe due to at least seven climate impacts in the energy sector. The GDP impact in warmer regions tends to be greater than in cooler regions, which benefit from less need for space cooling. Energy-related economic impact is anticipated to be negative for developing countries and positive in developed countries. Adaptation within the energy sector can lower the cost of climate change, but these results may be driven largely by assumption because specific policies have not been modeled in these macroeconomic impact studies. Results from some of the partial equilibrium models suggests that CGE modeling studies, which largely focus on changes in energy demand, may be neglecting some potentially costly impacts from extreme weather events such as drought (see, e.g., Box CC-WE), which, if modeled, may lead to greater GDP losses than reported thus far in the literature.

Much research is still needed to understand the implications of climate change and extreme weather on the energy sector and to identify cost-effective adaptation options. The best understood area is the implications of climate on energy demand. A comprehensive evaluation of a full range of supply-side climate change impacts and adaptation options for all aspects of energy infrastructure is needed. This information will lead to an improved assessment of climate impacts due to the use of better, empirically based assumptions about the relationship of climate impacts and the economy, as well as about the effectiveness of adaptation options.

10.3. Water Services

This section focuses on economic aspects of climate change in water-intensive sectors and infrastructure to provide water services. The climate change impacts on biophysical water system, including the engineering aspects of water infrastructure, are assessed in Chapter 3. There is a limited set of studies published in this area and conclusions are limited by the scope of information to date.

10.3.1. Water Infrastructure and Economy-Wide Impacts

Between the 1950s and the 1990s, the annual economic losses from large extreme events, including floods and droughts, increased 10-fold, with developing countries being hardest hit (Kabat et al., 2003). Over the past few decades, flood damage constitutes about a third of the economic losses inflicted by natural hazards worldwide (Munich Re, 2005). The economic losses associated with floods worldwide have increased by a factor of five between the periods 1950–1980 and 1996–2005 (Kron and Berz, 2007). In 1990–1996 alone, there were six major floods throughout the world in which the number of fatalities exceeded 1000, and 22 floods with losses exceeding US$1 billion each (Kabat et al., 2003). Although these increases are primarily due to several non-climatic drivers, climatic factors are also partly responsible (Kundzewicz et al., 2007). Chapter 4 of the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) provides a comprehensive look at the impacts of extreme events on water supply (IPCC, 2012) and flooding at a wide range of spatial scales.

Most of the studies examining the economic impacts of climate change on the water sector have been carried out at the local, national, or river-basin scale; and the global distribution of such studies is skewed toward developed countries (Schreider et al., 2000; Chen et al., 2001; Middelkoop et al., 2001; Choi and Fisher, 2003; Hall et al., 2005; Hurd and Rouhi-Rad, 2013). In other studies, the economic impacts of climate

variability on floods and droughts in developing countries were reported as substantial. These studies address climate variability; climate change may impact both mean and variability of the hydro-climatic system. The floods associated with the 1997–1998 El Niño and the drought associated with the 1998–2000 La Niña show a cost to Kenya of 11% and 16% of GDP, respectively (Mogaka et al., 2006). Floods and droughts are estimated to cost Kenya about 2.4% of GDP annually at mid-century, and water resources degradation a further 0.5% (Mogaka et al., 2006). For Ethiopia, economy-wide models incorporating hydrological variability show a drop in projected GDP growth by up to 38% compared to when hydrological variability is not included (World Bank, 2006). Syria is projected to experience reduction in economy-wide growth and incomes of urban households (Breisinger et al., 2013). However, it is not hydrological variability per se that causes the problem, but rather a lack of the necessary capacity, infrastructure, and institutions to mitigate the impacts (Grey and Sadoff, 2007). Similarly, future flood damages will depend not only on changes in the climate regime, but also on settlement patterns, land use decisions, flood forecasting quality, warning and response systems, and other adaptive measures (Pielke and Downton, 2000; Changnon, 2005; Ward et al., 2008). In many developing countries, water-related impacts are likely to be more pronounced with climate change (Chapter 3) and associated economic costs can be expected to be more substantial in the future, holding all other factors constant.

Climate change could increase the annual cost of flooding in the UK almost 15-fold by the 2080s under high emission scenarios. If climate change increased European flood losses by a similar magnitude, annual costs could increase by up to US$120 to 150 billion, for the same high emission scenarios (ABI, 2005). Feyen et al. (2012) project average annual damage in the EU to increase to US$18 to 28 billion by 2100 depending on the scenario, compared to US$8.5 billion today. Continental U.S. mean annual flood damages may increase by US$5 billion and US$12 billion in 2050 and 2100, respectively (Wobus et al., 2013). Ntelekos et al. (2010) estimate a range of US$7 to 19 billion, depending on the economic growth rate and the emissions scenarios. Dasgupta et al. (2010) report that by 2050 Bangladesh will face incremental cost to flood protection (against both sea and river floods) of US$2.6 billion initial costs and US$54 million annual recurring costs. Ward et al. (2008) found that the average annual costs to adapt to a 1-in-50-year river flood to range from US$3.5 to 6.0 billion per year for low- to upper-middle-income countries over the period 2010–2050 for the SRES A2 scenario.

10.3.2. Municipal and Industrial Water Supply

Municipal and industrial water supply economic systems are also impacted through changes in precipitation patterns and quantities. These impacts are evaluated as current costs of building in resiliency to the system to adapt to anticipated future changes. For example, the costs of adaptation to maintain supply and quality of water for municipal and industrial uses have been reported for the Assabet River near Boston (Kirshen et al., 2006), Toronto (Dore and Burton, 2001), and Quito (Vergara et al., 2007). Initial analysis indicates that adaptation measures may be beneficial for water infrastructure with an economic and engineering life of more than 25 years. Nassopoulos et al. (2012) suggest that neglecting to account for future climate change while designing water supply reservoirs can cost 0.2 to 2.8% of the net present value, based on analysis for Greece. For sub-Saharan Africa, adapting urban water infrastructure (storage facilities, wastewater, and additional supply infrastructure) to a 30% reduction in runoff could be US$2 to 5 billion per year (Muller, 2007). Climate change impacts on the Berg River in South Africa are estimated to account for 20% revenue loss for the water supply provider and 15.2% loss in social welfare (Callaway et al., 2012). For the Organisation for Economic Co-operation and Development (OECD), the cost of adaption in the water supply sector is 1 to 2% of base costs and would save US$6 to 12 billion per year (Hughes et al., 2010). U.S. impacts are estimated to be less than 1% of municipal and industrial welfare (Hurd et al., 2004; Strzepek et al., 2013). In Colorado, a 30% decrease in annual runoff will result in a 12% treatment cost increase and a 22% rise in residential costs (Towler et al., 2011).

Ward et al. (2010) estimate the costs of adaptation to climate change to ensure enough raw water to meet future industrial and municipal water demand for each country to 2050. Increased demand is assumed to be met through a combination of increased reservoir yield and alternative backstop measures. The global adaptation costs are estimated to be US$12 billion per year (0.04 to 0.06% of GDP), on top of US$73 billion per year to meet the needs of development, with 83 to 90% in developing countries. The highest costs are in sub-Saharan Africa, and may be as high as 16% of the global total. Adding adaptive measures to water infrastructure adds 10 to 20% to the total costs of developing countries meeting the water-related millennium goals (Ward et al., 2010).

10.3.3. Wastewater and Urban Stormwater

More frequent heavy rainfall events may overload the capacity of sewer systems and water and wastewater treatment plants more often, and increased occurrences of low flows will lead to higher pollutant concentrations. It is projected for USA in 2100 that national wastewater treatment costs will increase by US$0.6 to 8 billion per year (Henderson et al., 2013). The annual costs of urban stormwater system adaptation, averaged costs over 17 climate models simulating the SRES A2 emissions scenario, is US$3 billion per year in low- to upper-middle-income nations over the period 2010–2050 (Hughes et al., 2010). Adaptation costs estimates (for a 10-year, 24-hour storm in 2100) for various locations in the USA are relatively low; for example, US$135 million for Los Angeles, US$7 million for Boston, and US$40 million for Chicago (Neumann et al., 2013). Adapting bridges to altered urban floods could cost US$140 to 250 billion in the USA through the 21st century (Wright et al., 2012).

10.3.4. Inland Navigation

See Section 10.4.4.

10.3.5. Irrigation

Climate change impacts on the economics of irrigation reflect the anticipated change in temperature, precipitation, and agricultural demand and practices. Assessments of surface, ground, and gray water irrigation

supplies are addressed in Chapter 3; implications for food production are covered in Chapter 7. By 2080, the global annual costs of additional irrigation water withdrawals for currently existing irrigated land are estimated at US$24 to 27 billion (Fischer et al., 2007). The global cost of improved irrigation efficiency to maintain yields is US$1.5 to 2.0 billion per year for the A2 scenario in developing countries in 2050 (Nelson et al., 2009).

Adaptation to maintain agricultural production in Ethiopia would be best achieved by better soil water management with the application of integrated irrigation and drainage systems, improved irrigation efficiency, and research related to on-farm practices; adaptation costs range from US$68 million per year for the dry scenario dominated by irrigation, to US$71 million per year under the wet scenario dominated by drainage (Strzepek et al., 2010).

10.3.6. Nature Conservation

Climate change is expected to worsen many forms of water pollution, including the load of sediments, nutrients, dissolved organic carbon, pathogens, pesticides, and salt, as well as thermal pollution, increased precipitation intensity, and low flow periods (Kundzewicz et al., 2007). Future water demands for nature conservation will be different than today's (see Chapter 4). There is no published assessment of the economic implications.

10.3.7. Recreation and Tourism

Tourism and recreation use substantial amounts of water but the implications of climate change-induced changes in tourism and recreation on water demand have yet to be quantified. See Section 10.6.

10.3.8. Water Management and Allocation

Water scarcity and competition for water, driven by institutional, economic, or social factors, may mean that water assumed to be available for a sector is not and thus economic analyses at the sectoral level are crucial; inter-sectoral and economy-wide assessments are needed for comprehensive economic impacts of water services.

Changes in water availability, demand, and quality due to climate change would impact water management and allocation decisions. Traditionally, water managers and users have relied on historical experience when planning water supplies and distribution (Adger et al., 2007; UNFCCC, 2007). Under a changing climate, existing allocations may no longer be appropriate. Arndt et al. (2012) examine the implications of alternative development paths and water allocations to suggest climate-smart development strategies in Africa; under stress situations, allocations of water to energy-generation and irrigation may have economy-wide welfare implications. Water resource-related climate change impacts on the U.S. economy measured as cumulative undiscounted welfare changes over the 21st century range from plus US$3 trillion for wet scenarios to minus US$13 trillion under dry scenarios (in US$^{2000}; Henderson et al., 2013).

10.3.9. Summary

Globally, greenhouse gas-induced increases in flooding and droughts may have substantial economic impacts (capital destruction, sectoral disruption) while estimates of adaptation costs (construction, defensive investment) range from relatively modest to relative high levels (see Box CC-WE).

10.4. Transport

The impact of climate change and sea level rise on transport has received qualitative, but limited quantitative, focus in the published literature. The impact depends greatly on the climatic zone the infrastructure is in and how climate change will be manifest. There are three major zones:

Geographic Zone	*Changes in Climate Expected to Impact Vulnerability*
Freezing/Frost Zone	Permafrost, freeze-thaw cycles, precipitation, flooding, SLR, and storms (coastal)
Temperate Zone	Precipitation intensity, flooding, maximum daily precipitation, SLR, and storms (coastal)
Tropical Zone	Precipitation intensity, flooding, maximum daily precipitation, SLR, and storms (coastal)

As detailed in Sections 10.4.1, 10.4.2, 10.4.4, and 10.4.5, several studies have explored the potential impacts of climate change on the transport sector—focusing, for example, on safety or disruptions of service. Quantitative, economic analyses of the impact on physical infrastructure include Larsen et al. (2008), Chinowsky et al. (2010, 2011), and Hunt and Watkiss (2010) and on wider economic implications, Arndt et al. (2012).

Adaptation options for each sub-sector of transport infrastructure have been studied. Existing literature includes CCSP (2008) and Chinowsky et al. (2011), with proposed strategies ranging from technical to political, including focus on upgraded design specifications during new construction, retrofitting structures, and modified land use planning in coastal areas. Adaptation and resiliency to extreme events is of particular interest as they may have a cascading impact, in that the loss of critical infrastructure assets will negatively affect the recovery and resiliency of a community (Kirshen et al., 2008a,b).

10.4.1. Roads

Studies on the direct effects of climate change on road networks are focused primarily on qualitative predictions and surveys concerning impacts on road durability (National Research Council, 2008; Koetse and Rietveld, 2009; Eisenack et al., 2012; Ryley and Chapman, 2012); with some studies of the quantitative effects (Nemry and Demirel, 2012; Chinowsky et al., 2013). Noted impacts from changes in precipitation and temperature include changes in required road maintenance. These quantitative studies focus on specific impacts such as maintenance in an effort to quantify the long-term costs that need to be assumed by national and regional road agencies. Examples of the metrics used include kilometers of roads lost over time, redistribution requirements of transport funds, and benefits from adaptation on long-term maintenance.

Chapter 8 addresses the indirect effects of climate change on roads in the areas of congestion and safety. As an example, increases in heavy precipitation events will negatively affect driving safety through decreased driver visibility and changing surface conditions (Qiu and Nixon, 2008).

Paved road degradation is directly related to heat stress that can lead to softening of the pavement as temperatures exceed design thresholds (Lavin, 2003), and an increase in the number of freeze-thaw cycles impacts both the base and pavement surface (FHWA, 2006). The melting of permafrost in northern climates, as well as increased precipitation and flooding, threaten the integrity of road base and sub-bases (Qin et al., 2005). Drainage presents a specific problem for urban areas that experience rainfall above their built capacity and will influence new design standards and costs for urban transport (City of Chicago, 2008; Hunt and Watkiss, 2010; Lemmen and Warren, 2010). Increased fire danger from droughts could also pose a threat to roads.

Unpaved roads are vulnerable to a number of climate-based factors especially to increasingly intense precipitation, leading to wash out and disruption of service (Chinowsky and Arndt, 2012). Increased precipitation in agricultural areas may have negative economic impacts in addition to the direct impact on infrastructure. In cold climates, temporary winter roads are susceptible to warming and associated lower connectivity of rural areas and reduced economic activity in northern climates (Mills and Andrey, 2002). Warming could imply that ice roads can no longer be maintained.

Bridges form a core component of any nation's infrastructure. However, highway bridges that cross water, ubiquitous to most highway networks, are exposed to climate changes via flood events and associated changes in long-term flow regimes. The potential disruptions that could occur due to the loss of or damage to these bridges are numerous. Estimates in the USA range from US$140 to 250 billion to address adaptation requirements for bridge infrastructure over the next 50 years (Wright et al., 2012). Similarly, European estimates range from US$350 to 500 million per year to adapt bridge infrastructure (Nemry and Demirel, 2012). Once again, the potential cascading effects of these failures will affect the economic conditions of multiple sectors.

10.4.2. Rail

Rail beds are susceptible to increases in precipitation, flooding and subsidence, SLR, extreme events, and incidence of freeze-thaw cycles (Nemry and Demirel, 2012). In northern climates, the melting of permafrost (URS, 2010) may lead to ground settlement, undermining stability (Larsen et al., 2008). Increased temperatures pose a threat to rail through thermal expansion. In urban areas, increased temperatures pose a threat to underground transport systems that will see a burden on increased need for cooling systems (Hunt and Watkiss, 2010). For example, US$290 million has been allocated to finding a workable solution for increasing the capacity of London's underground cooling system (Arkell and Darch, 2006). The complexity of addressing rail infrastructure is increased through differences in design specifications, multiple types of rail and materials used, and uncertainty about the changes in future temperatures.

10.4.3. Pipeline

Increases in precipitation and temperature affect pipelines through scouring of base areas and unearthing of buried pipelines (URS, 2010), compromised stability of bases built on permafrost, and increases in necessary maintenance (National Research Council, 2008; URS, 2010). Temperature increase can result in thermal expansion of the pipelines, causing cracking at material connection points. In tropical areas, increased precipitation may lead to landslides that can compromise pipeline infrastructure (Sweeney et al., 2005). There has been no economic assessment of the impacts.

10.4.4. Shipping

Impacts on inland navigation vary widely due to projected rise or fall in water levels. Overall, the effects on inland navigation are projected to be negative, and are region specific.

Increased frequency of flood periods will stop ship traffic on the Rhine more often; longer periods of low flow will also increase the average annual number of days during which inland navigation is hampered or stagnates due to limited load carrying capacity of the river; channel improvements can only partly alleviate these problems (Middelkoop et al., 2001). Economic impact could be substantial given the value of navigation on the Rhine (Krekt et al., 2011). See Chapter 23.

Virtually all scenarios of future climate change project reduced Great Lakes water levels and connecting channel flows, mainly because of increased evaporation resulting from higher temperatures. The potential economic impact may result in reductions in vessel cargo capacities and increases in shipping costs. The lower water levels predicted as a result of a doubling of atmospheric CO_2 could increase annual transportation costs by 29%, while more moderate climate change could result in a 13% increase in annual shipping costs. The impacts vary across commodities and routes (Millerd, 2010).

Warming leads to increased ice-free navigation and a longer shipping season, but also to lower water levels from reduced runoff (Lemmen and Warren, 2010). In cold regions, increased days of ice-free navigation and a longer shipping season could impact shipping and reduce transportation costs (National Research Council, 2008; Koetse and Rietveld, 2009; UNCTAD, 2009; UNECE and UNCTAD, 2010), although movement in ice waters such as the Canada Arctic sea could become more difficult (Wilson et al., 2004; Stewart et al., 2007).

Ports will be affected by climate changes including higher temperatures, SLR, increasingly severe storms, and increased precipitation (Becker et al., 2011; Nursey-Bray and Miller, 2012). However, (the need to prioritize) adaptation of ports has been overshadowed by a focus on potential impacts. Training of port personnel is needed to begin the adaptation process. More than US$3 trillion in port infrastructure assets in 136 of the world's largest port cities are vulnerable to weather events (CCSP, 2008; UNCTAD, 2009; UNECE and UNCTAD, 2010).

Increased storminess in certain routes may raise cost of shipping through additional safety measures or longer routes that are less storm

prone (UNCTAD, 2009; UNECE and UNCTAD, 2010). Transport costs would increase or new routes sought if storms disrupt supply chains by destroying port infrastructure connecting road or rail (Becker et al., 2011). Increased storminess may also affect passage through lock systems (CCSP, 2008; UNCTAD, 2009). Increased storminess may increase maintenance costs for ships and ports and result in more frequent weather-related delays.

10.4.5. Air

Hotter air is less dense. In summer months, especially at airports located at high altitudes, this may result in limitations for freight capacity, safety issues, and weather-related delays, unless runways are lengthened (National Research Council, 2008; Pejovic et al., 2009). Chapman (2007) suggests that technological innovations will negate the challenges posed by extreme temperatures.

Increased storminess at airports, particularly those located in coastal regions, may increase the number of weather-related delays and cancellations (Pejovic et al., 2009; Lemmen and Warren, 2010) and increase maintenance and repair costs (Gusmao, 2010). Clear-air turbulence will increase in the Atlantic corridor, leading to longer and bumpier trips (Williams and Joshi, 2013). The impact of climate change on airport pavement is very similar to paved roads (DOT, 2002; Allard et al., 2007). The effect of temperature and increased precipitation intensity on airports imposes a risk to the entire facility if pavements are not adapted to these increases (Pejovic et al., 2009).

10.5. Other Primary and Secondary Economic Activities

This section assesses the impact of climate change on primary (agriculture, mining) and secondary economic activities (manufacturing, construction), unless they are discussed elsewhere in the chapter or the report.

10.5.1. Primary Economic Activities

Primary economic activities (e.g., agriculture, forestry, fishing, mining) are particularly sensitive to the consequences of climate change because of their immediate dependence on the natural environment. In some regions, these activities dominate the economy.

10.5.1.1. Crop and Animal Production

Chapters 7 and 9 assess the impact of climate change on agriculture, including the effects on (international) markets for crops.

10.5.1.2. Forestry and Logging

Chapter 4 assesses the biophysical impact of climate change on forestry. Including adaptation in forest management, climate change will accelerate tree growth. This will reduce prices to the benefit of consumers everywhere. Low to mid latitude producers will benefit too as they switch to short-rotation forest plantations. Mid- to high-latitude producers will be hurt by lower prices while their productivity increases only modestly (Sohngen and Mendelsohn, 1997, 1998; Sohngen et al., 2001; Perez-Garcia et al., 2002; Lee and Lyon, 2004; Seppala et al., 2009). The value of the forest land in Europe would fall between 14 and 50% by 2100 (Hanewinkel et al., 2013). Different trees will be affected differently (Aaheim et al., 2011a,b). Higher biomass prices differentially impact different forest-based industries (Moiseyev et al., 2011).

10.5.1.3. Fisheries and Aquaculture

Chapter 4 assesses impacts of climate change on freshwater ecosystems, and Chapters 5, 6, and 30 on marine ecosystems. These assessments include the effects on commercially valuable fish stocks, but exclude the effects on markets. Adaptation and markets will substantially change the effect of climate change on fisheries (Link and Tol, 2009; Yazdi and Fashandi, 2010).

Allison et al. (2009), using an indicator-based approach, analyzed the vulnerability of capture fishery of 132 economies. Incongruously, they find that the sign and size of climate-driven change for particular fish stocks and fisheries are uncertain but are expected to lead to either increased economic hardship or missed opportunities for development in countries that depend on fisheries but lack the capacity to adapt. A major part of the gross turnover of nine key fish and cephalopod species in the Bay of Biscay remains potentially unaffected by climate change (Le Floc'h et al., 2008). In contrast, Iberian-Atlantic sardine biomass and profitability declines due to climate change (Garza-Gil et al., 2011). The economic impact of climate change on fisheries is dominated by the impact of management regime and market (Eide and Heen, 2002; McGoodwin, 2007; Eide, 2008; McIlgorm, 2010; Merino et al., 2010).

Ocean acidification has a range of impacts on the biological systems (Doney et al., 2009), but the studies on the economic impacts of ocean acidification are rare (Cooley and Doney, 2009; Hilmi et al., 2013). Using a partial equilibrium model, Narita et al. (2012) estimate the economic impact of ocean acidification on shellfish. By the turn of this century the aggregate cost could be greater than US$100 billion.

10.5.1.4. Mining and Quarrying

Climate change will affect exploration, extraction, production, and shipping in the mining and quarrying industry (Pearce et al., 2011). An increase in climate-related hazards (such as forest fires, flooding, windstorm) affects the viability of mining operations and potentially increases operating, transportation, and decommissioning costs.

Most infrastructure was built based on presumption of a stable climate, and is thus not adapted to climate change (Ford et al., 2010, 2011; Pearce et al., 2011). Damigos (2012) estimates the damages due to climate change under the SRES A1B scenario for the period 2021–2050 of the extent of US$0.8 billion for the Mediterranean Region. Note that other factors such as research and development might influence the viability of mining operations by lowering the cost of adaptation.

10.5.2. Secondary Economic Activities

10.5.2.1. Manufacturing

Climate change will impact manufacturing through three channels. First, climate change affects primary economic activities (see Section 10.5.1), and this means that prices and qualities of inputs are different. Second, the supply chain is affected, or the quality of the product. The impact of climate change on energy demand is well understood (see Section 10.2). Using a biophysical model of the human body, Kjellstrom et al. (2009) project labor productivity to fall, particularly of manual labor in humid climates. Labor productivity losses will be accentuated by increased incidences of malaria and vector-borne diseases. Note that the loss in labor productivity can be offset by the technological progress. Hübler et al. (2008) uphold the finding with a German case study, and Hsiang (2010) corroborates it with a statistical analysis of weather data and labor productivity in the Caribbean for 1970–2006. Some manufacturing activity is location specific, perhaps because it is tied to an input or product market, and will thus have to cope with the current and future climate; other manufacturing has discretion over its location (and hence its climate). Third, climate change affects the demand for products. This is pronounced for manufactures that supply primary sectors (Kingwell and Farré, 2009) and construction material (see Section 10.5.2.2). Unfortunately, there are only a few studies that quantify these effects (see Section SM10.1 of the on-line supplementary material).

10.5.2.2. Construction and Housing

Climate and climate change affect construction in three ways. First, weather conditions are one of the key factors in construction delays and thus costs. Climate change will change the length of the building season. In addition, precipitation affects the cost of construction through temporary flood protection (coffer) structures, slope stabilization management, and dewatering of foundations. There are adaptation measures that may reduce some of the costs. Apipattanavis et al. (2010) show a reduction in the expected value of road construction delays and associated costs. Second, buildings and building materials are designed and selected to withstand a particular range of weather conditions. As climate changes, design standards will change too. Exterior building components including windows, roofing, and siding are all specified according to narrow environmental constraints. Climate change will introduce conditions that are outside the prescribed operating environment for many materials, resulting in increased failures of window seals, increased leaks in roofing materials, and reduced lifespan of timber or glass-based cladding materials. Similarly, the interior building systems that allow for proper airflow in a facility face significant issues with climate change. For example, the increases in temperature and precipitation will lead to increased humidity as well as indoor temperatures. This requires increased airflow in facilities such as hospitals, schools, and office buildings—that is, upgrades to air conditioning and fan units, and perhaps further renovations that may be significant in scope and cost. Third, a change in the pattern of natural disasters will imply a change in the demand for rebuilding and repair. Unfortunately, these impacts have yet to be quantified (Hertin et al., 2003). Note that the direction and magnitude of the effect on construction and housing costs will possibly vary geographically. Cost impacts due to changing precipitation and storms patterns (magnitude, frequency, and/or variation) will vary as these changes are expected to vary by region as well. Air to air heat exchangers, heat recovery ventilators, and dehumidifiers and other technologies may be useful in adapting indoor air quality.

10.6. Recreation and Tourism

Recreation and tourism is one of the largest sectors of the world economy. In 2011, it accounted for 9% of global expenditure, and employed 260 million people (WTTC, 2011). Supply of tourism services is the dominant activity in many regional economies.

Recreation and tourism encompass many activities, some of which are more sensitive to weather and climate than others: compare sunbathing to angling, gambling, business seminars, family visits, and pilgrimage. Climate change would affect the place, time, and nature of these activities.

There is a large literature on the impact of climate change on tourism (Gössling et al., 2012; Scott et al., 2012a; Pang et al., 2013). Some studies focus on the changes in the behavior of tourists—that is, the demand for recreation and tourism services (see Section 10.6.1). Other studies look at the implications for tourist operators and destinations—that is, the supply of recreation and tourism services (see Section 10.6.2). A few studies consider the interactions between changes in supply and demand (see Section 10.6.3).

10.6.1. Recreation and Tourism Demand

Conventionally, recreation does not involve an overnight stay whereas tourism does. That implies that recreation, unlike tourism, is done close to home. Whereas tourists, to a degree, chose the climate of their holidays, recreationists do not (although climate is a consideration in the choice where to live). Tourists would adapt to climate change by changing the region, timing, and activities of their holidays; recreationists would adapt only timing and activities (Becken and Hay, 2007).

10.6.1.1. Recreation

There has been no research on systematic differences of recreational behavior due to differences in climate at large spatial scales. The impact of climate change on recreation is therefore largely unknown. The economic impact is probably limited, as people will tend to change the composition rather than the level of their time and money spent on recreation. For instance, Shaw and Loomis (2008) argue that climate change would increase boating, golfing, and beach recreation at the expense of skiing.

There are case studies that indicate the impact of climate change on recreation. Buckley and Foushee (2012) find a trend toward earlier visits to U.S. national parks between 1979 and 2008. They argue this is due to climate change, but do not rigorously test this hypothesis nor control for other explanations. Whitehead et al. (2009) find a substantial decrease in the recreational value of sea shore fishing in North Carolina due to

SLR. Daugherty et al. (2011) conclude that climate change will make it more difficult to guarantee adequate water levels for boating and angling in artificial reservoirs. Pouta et al. (2009) project a reduction in cross-country skiing in Finland, particularly among women, the lower classes, and urban dwellers. Shih et al. (2009) find that weather affects the demand for ski lift trips. Hamilton et al. (2007) highlight the importance of "backyard snow" to induce potential skiers to visit ski slopes. One could expect people to adopt other ways of enjoying themselves but such alternatives were excluded from these studies.

There are positive effects too (Richardson and Loomis, 2005). Scott and Jones (2006, 2007) foresee an increase in golf in Canada due to climate change. Kulshreshtha (2011) sees positive impacts on recreation on the Canadian Prairies, and Coombes et al. (2009) predict an increase in beach tourism in East Anglia. Graff Zivin and Neidell (2010) find that people recreate indoors when the weather is inclement.

Scott et al. (2007) estimate the relationship between visitors to Waterton Lakes National Park and weather variables for 8 years of monthly observations, and use this to project an increase in visitor numbers due to climate change. A survey among current visitors indicates that a deterioration of the quality of nature would reduce visitor numbers. Jones et al. (2006) study the impact of climate change on three festivals in Ottawa. They argue for heat wave preparedness for Canada Day, find that skating on natural ice may become impossible for Winterlude, and that the dates of the Tulip Festival may need to be shifted to reflect changing phenology.

10.6.1.2. Tourism

Climate (Becken and Hay, 2007; WTO and UNEP, 2008) and weather (Álvarez-Díaz and Rosselló-Nadal, 2010; Rosselló-Nadal et al., 2010; Rossello, 2011; Førland et al., 2012; Day et al., 2013; Falk, 2013) are important factors in tourist destination choice, and the tourist sector is susceptible to extreme weather (Forster et al., 2012; Hamzah et al., 2012; Tsai et al., 2012). Eijgelaar et al. (2010), for instance, argue that so-called "last chance tourism" is a strong pull for tourists to visit Antarctica to admire the glaciers while they still can. Farbotko (2010) and Prideaux and Mcnamara (2012) use a similar mechanism to explain the rise in popularity of Tuvalu as a destination choice. Huebner (2012) find no impact of future climate change on current travel choices. Taylor and Ortiz (2009) show that domestic tourists in the UK often respond to past weather; the hot summer of 2003 had a positive impact on revenues of the tourist sector. Denstadli et al. (2011) find that tourists in the Arctic do not object to the weather in the Arctic; Gössling et al. (2006) reaches the same conclusion for tourists on Zanzibar; and Moreno (2010) for tourists in the Mediterranean.

There are a number of biometeorological studies of the impact of climate change on tourism. Yu et al. (2009a) find that Alaska has become more attractive over the last 50 years and Florida less attractive to tourists. Yu et al. (2009b) conclude that the climate for sightseeing has improved in Alaska, while the climate for skiing has deteriorated. Matzarakis et al. (2010) construct a composite index of temperature, humidity, wind speed, and cloud cover, and use this to map tourism potential. Lin and Matzarakis (2008, 2011) apply the index to Taiwan POC and eastern China. Endler and Matzarakis (2010a,b, 2011) use an index to study the Black Forest in Germany in detail, highlighting the differences between summer and winter tourism, and between high and low altitudes (Endler et al., 2010). Zaninović and Matzarakis (2009) and Matzarakis and Endler (2010) use this method to study Freiburg and Hvar. Matzarakis et al. (2007) project this potential into the future, finding that the Mediterranean will probably become less attractive to tourists. Hein et al. (2009), Perch-Nielsen et al. (2009), Giannakopoulos et al. (2011), Amelung and Moreno (2012), and Amengual et al. (2012) reach the same conclusion, but also point out that Mediterranean tourism may shift from summer to the other seasons. Giannakopoulos et al. (2011) note that coastal areas in Greece may be affected more than inland areas because, although temperature would be lower, humidity would be higher. Moreno and Amelung (2009), on the other hand, conclude that climate change will not have a major impact (before 2050) on beach tourism in the Mediterranean because sunbathers like it hot (Moreno, 2010; Rutty and Scott, 2010). Amelung et al. (2007) use a weather index for a global study of the impact of climate change on tourism, finding shifts from equator to pole, summer to spring and autumn, and low to high altitudes. Perch-Nielsen (2010) combines a meteorological indicator of exposure with indicators of sensitivity and adaptive capacity, and uses this to rank the vulnerability of beach tourism in 51 countries. India stands out as the most vulnerable, and Cyprus as the least vulnerable.

The main criticism of most biometeorological studies is that the predicted gradients and changes in tourism attractiveness have rarely been tested to observations of tourist behavior. De Freitas et al. (2008) validate their proposed meteorological index to survey data. Moreno et al. (2008) and Ibarra (2011) use beach occupancy to test meteorological indices for beach tourism. Gómez-Martín (2006) tests meteorological indices against visitor numbers and occupancy rates. All four studies find that weather and climate affects tourists, but in a different way than typically assumed by biometeorologists.

Maddison (2001) estimates a statistical model of the holiday destinations of British tourists, Lise and Tol (2002) for Dutch tourists, Bujosa and Rosselló (2012) for Spanish tourists in Spain, and Bigano et al. (2006) for international tourists from 45 countries. These models control for as many other variables as possible; their focus on the average tourist may be misleading, and their representation of climate may be oversimplified (Gössling and Hall, 2006). Tourists have a clear preference for the climate that is currently found in southern France, northern Italy, and northern Spain. People from hot climates care more about the climate in which they spend their holidays than people from cool climates. Whereas (Bigano et al., 2006) find regularity in *revealed* preferences, Scott et al. (2008b) find pronounced differences in *stated* preferences between types of people.

Bigano et al. (2007) and Hamilton et al. (2005a,b) construct a simulation model of domestic and international tourism and climate change (but not SLR), considering the simultaneous change in the attractiveness of all potential holiday destinations (Dawson and Scott, 2013); Hamilton and Tol (2007) downscale these national results to the regions of selected countries. Two main findings emerge. First, climate change would drive tourists to higher latitudes and altitudes. International tourist arrivals would fall, relative to the scenario without warming, in

hotter countries, and rise in colder countries. Tourists from northwestern Europe, the main origin worldwide of international travelers at present, would be more inclined to spend the holiday in their home country, so that the total number of international tourists falls. Second, the impact of climate change is dominated by the impact of population growth and, particularly, economic growth. In the worst affected countries, climate change slows down, but nowhere reverses, growth in the tourism sector.

10.6.2. Recreation and Tourism Supply

Studies on the supply side often focus on ski tourism. Warming is expected to raise the altitude of snow-reliable ski resorts, and fewer resorts will be snow reliable (Dawson et al., 2009; Hendrikx et al., 2012, 2013; Steger et al., 2012). Snowmobiling will be negatively affected too (Mcboyle et al., 2007; Scott et al., 2008a). Artificial snow-making cannot fully offset the loss in natural snowfall (Elsasser and Bürki, 2002; Scott et al., 2006; Hoffmann et al., 2009), particularly in lower areas (Wolfsegger et al., 2008; Morrison and Pickering, 2012; Schmidt et al., 2012), and water scarcity and the costs of snowmaking will be increasingly large problems (Scott et al., 2003, 2007; Steiger and Mayer, 2008; Hendrikx and Hreinsson, 2012; Matzarakis et al., 2012; Pons-Pons et al., 2012); skiers prefer natural over artificial snow (Pickering et al., 2010). Tourism alternatives to skiing or non-tourism alternatives need to be considered as a source of economic development (Bicknell and Mcmanus, 2006; Moen and Fredman, 2007; Scott and McBoyle, 2007; Tervo, 2008; Bourdeau, 2009; Potocka and Zajadacz, 2009; Hill et al., 2010; Pickering and Buckley, 2010; Steiger, 2010; Serquet and Rebetez, 2011; Landauer et al., 2012; Matzarakis et al., 2012). Other socioeconomic trends dominate the impact of climate change (Hopkins et al., 2012; Steiger, 2012).

Other studies consider beach tourism. Scott et al. (2012b) highlight the vulnerability of coastal tourism facilities to SLR. Hamilton (2007) finds that tourists are averse to artificial coastlines, so that hard protection measures against SLR would reduce the attractiveness of an area. Raymond and Brown (2011) survey tourists on the Southern Fleurieu Peninsula. They conclude that tourists who are there for relaxation worry about climate change, particularly SLR, while tourists who are there to enjoy nature (inland) do not share that concern. Becken (2005) finds that tourist operators have adapted to weather events, and argues that this helps them to adapt to climate change. Belle and Bramwell (2005) find that tourist operators on Barbados are averse to public adaptation policies. Uyarra et al. (2005) find that tourists on Barbados would consider holidaying elsewhere if there is severe beach erosion. Buzinde et al. (2010a,b) find that there is a discrepancy between the marketing of destinations as pristine and the observations of tourists, at least for Mexican beach resorts subject to erosion. They conclude that tourists have a mixed response to environmental change, contrary to the officials' view that tourists respond negatively. Jopp et al. (2013) find that an increase in tourism in the shoulder season may offset losses in the peak season in Victoria.

Some studies focus on nature tourism. Cavan et al. (2006) find that climate change may have a negative effect on the visitor economy of the Scottish uplands as natural beauty deteriorates through increased wild fires. Saarinen and Tervo (2006) interviewed nature-based tourism operators in Finland, and found that about half of them do not believe that climate change is real, and that few have considered adaptation options. Nyaupane and Chhetri (2009) argue that climate change would increase weather hazards in the Himalayas and that this would endanger tourists. Uyarra et al. (2005) find that tourists on Bonaire would not return if coral were bleached. Hall (2006) finds that small tourist operators in New Zealand do not give high priority to climate change, unless they were personally affected by extreme weather in recent times. The interviewed operators generally think that adaptation is a sufficient response to climate change for the tourism sector. Klint et al. (2012) find that tourist operators in Vanuatu give low priority to adaptation to climate change and Jiang et al. (2012) find Fiji poorly prepared. Saarinen et al. (2012) find that tourist operators in Botswana think that climate change would not affect them. Wang et al. (2010) note that glacier tourism is particularly vulnerable to climate change, highlighting the Baishiu Glacier in China. Brander et al. (2012) estimate the economic impacts of ocean acidification on coral reefs under four IPCC marker scenarios using value transfer function approach and find that the annual economic impacts increase rapidly overtime, though it remains a small fraction of total income.

While the case studies reviewed above provide rich detail, it is hard to draw overarching conclusions. A few studies consider all aspects of the impact of climate change for particular countries or regions (Ren Guoyu, 1996; Harrison et al., 1999). In France, the Riviera may benefit because it is slightly cooler than the competing coastal resorts in Italy and Spain; the Atlantic Coast, although warming, would not become more attractive because of increased rainfall; it is not probable that the increase in summer tourism in the mountains would offset the decrease in winter tourism (Ceron and Dubois, 2005). In the Great Lakes regions, there is a reduced tourism potential in winter but increased opportunities in summer (Dawson and Scott, 2010). Tourist operators in Australia find the uncertainty about climate change too large for early investment in adaptation (Turton et al., 2010).

10.6.3. Market Impacts

There are only two papers that consider the economic impacts of rather stylized climate change-induced changes in tourism supply and demand. Both studies use a global computable general equilibrium model, assessing the effects on the tourism sector as well as all other markets. Berrittella et al. (2006) consider the consumption pattern of tourists and their destination choice. They find that the economic impact is qualitatively the same as the impact on tourist flows (discussed above): Colder countries benefit from an expanded tourism sector, and warmer countries lose. They also find a drop in global welfare, because of the redistribution of tourism supply from warmer (and poorer) to colder (and richer) countries.

Bigano et al. (2008) extend the analysis with the implications of sea level rise. The impact on tourism is limited because coastal facilities used by tourists typically are sufficiently valuable to be protected against SLR. The economic impacts on the tourism sector are reinforced by the economic impacts on the coastal zone; the welfare losses due to the impact of climate change on tourism are larger than the welfare losses due to SLR.

10.7. Insurance and Financial Services

10.7.1. Main Results of the Fourth Assessment Report and IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation on Insurance

More intense or frequent weather-related disaster would affect property insurance, of which coverage is expanding with economic growth (WGII AR4 Section 7.4.2.2.4). Insurability can be preserved through risk-reducing measures. Adaptation to climate change can be incentivized through risk-commensurate insurance premiums. Improved risk management would further financial resilience (WGII AR4 Sections 7.4.2.2.4, 7.6.3). Insurance is linked to disaster risk reduction and climate change adaptation, because it enables recovery, reduces vulnerability, and provides knowledge and incentives for reducing risk (IPCC, 2012).

10.7.2. Fundamentals of Insurance Covering Weather Hazards

Insurance is organized either through private markets, publicly, or public-private partnerships. It internalizes catastrophe risk costs prior to catastrophic events, reducing the economic impact of weather-related and other disasters to individuals, enterprises, and governments—thus stabilizing income and consumption, and decreasing societal vulnerability (Melecky and Raddatz, 2011; see also Section 17.5.1). Insurance is based on the law of large numbers: the larger the portfolio of uncorrelated and relatively small risks, the more accurately the average loss per policy can be predicted and charged accordingly, allowing for a lower premium than with a smaller ensemble. Besides spreading risk over a diversified insured population, insurance spreads risk over time. However, weather-related disasters such as floods simultaneously affect many, and thus violate the principle of uncorrelated risks. Consequently, large losses are much more probable, the loss variance is greater, and the tail risk is higher (Kousky and Cooke, 2012).

If insurance coverage is to be maintained, insurers would need more risk-based capital to indemnify catastrophic losses and remain financially solvent. This coverage is purchased in the reinsurance and capital markets. The capital costs account for a substantial portion of premiums and the affordability and viability of weather insurance are subjects of ongoing research given future climate change (Charpentier, 2008; Clarke and Grenham, 2012; Maynard and Ranger, 2012).

Increasing volatility and burden of losses in many regions are expected to fundamentally impact the industry, leading insurers to adapt their business to the changing risk (Herweijer et al., 2009; Phelan et al., 2011; Mills, 2012; Paudel, 2012). However, prevailing short-term contracts facilitate adaptation to changing circumstances (Botzen et al., 2010a).

10.7.3. Observed and Projected Insured Losses from Weather Hazards

Direct and insured losses from weather-related disasters have increased substantially in recent decades, both globally and regionally (Bouwer et al., 2007; Crompton and McAneney, 2008; IPCC, 2012; Munich Re, 2013; Smith and Katz, 2013; Swiss Re, 2013c). Global insured weather-related losses in the period 1980–2008 increased by US^{2008}1.4 billion per year on average (Barthel and Neumayer, 2012). As a rule, insured loss figures are more accurate than direct economic loss estimates, because insurance payouts are closely monitored. Often they are the basis for estimates of direct overall losses (Kron et al., 2012; Smith and Katz, 2013). Economic growth, including greater concentrations of people and wealth in periled areas and rising insurance penetration, is the most important driver of increasing losses.

Growth-induced changes in past losses are removed by normalizing to current levels of destructible wealth. So far, only one study analyzes normalized global weather-related insured losses (Barthel and Neumayer, 2012), but the period is too short (1990–2008) to support a meaningful analysis of trends. A few studies focus on specific perils and regions, in particular Australia, USA, and Europe. Trends were detected for the USA and Germany, but not for Australia and Spain (Table 10-4). Such trends can be influenced by changing damage sensitivities, adaptive measures, different normalization, and changes in insurance—besides changing hazards (Crompton and McAneney, 2008; Bouwer, 2011; Barthel and Neumayer, 2012; IPCC, 2012). Prevention measures such as flood control structures or improved building standards would offset an increase in hazard (Kunreuther et al., 2009, 2012). Given such confounding factors, it can be challenging to estimate to what degree developments in losses convey a climate signal (IPCC, 2012; Kron, 2012). Nonetheless, normalized direct natural disaster losses have already been demonstrated to properly

Frequently Asked Questions

FAQ 10.2 | How does climate change impact insurance and financial services?

Insurance buys financial security against, among other perils, weather hazards. Climate change, including changed weather variability, is anticipated to increase losses and loss variability in various regions through more frequent and/or intensive weather disasters. This will challenge insurance systems to offer coverage for premiums that are still affordable, while at the same time requiring more risk-based capital. Adequate insurance coverage will be challenging in low- and middle-income countries. Other financial service activities can be affected depending on the exposure of invested assets/loan portfolios to climate change. This exposure includes not only physical damage but also regulatory/reputational effects, liability, and litigation risks.

reflect climate variability on various time scales (Pielke and Landsea, 1999; Welker and Faust, 2013).

Studies analyzing changes in climate variables and insured losses in parallel are still rare. Variability and mean level of thunderstorm-related insured losses in the USA in the period 1970–2009 have substantially increased, while meteorological thunderstorm forcing has risen in parallel (Sander et al., 2013). The number of days that a regional insurer in southwest Germany sustains hail losses displays an upward trend since 1986, while meteorological severe storm indicators also show upward trends (Kunz et al., 2009). Although more studies find increases of large hail in Europe, general data and monitoring issues hindered assessing more than *low confidence* in observed meteorological trends (WGI AR5 Section 2.6.2.4). Corti et al. (2009) found an increase in modeled and partly observed insured subsidence losses in France over the period 1961–2002, consistent with a *likely* increase in dryness in Mediterranean regions (WGI AR5 Section 2.6.2.3). The observed rise in U.S. normalized insured flood losses (Barthel and Neumayer, 2012) may partly correspond to *very likely* increased heavy precipitation events in central North America (WGI AR5 Section 2.6.2.1), while the evidence for climate-driven changes in river floods is not compelling (WGI AR5 Section 2.6.2.2). Declining anthropogenic aerosol emissions may partly explain the recent upswing in hurricane hazard and losses (WGI AR5 Sections 2.6.3, 14.6; Table 10-4). Apart from detection, loss trends have not been conclusively attributed to anthropogenic climate change; most such discussions are not based on scientific attribution methods.

Many GCM-based projection studies agree that extreme winter storm wind speeds fall in the Mediterranean and increase in west, central, and northern Europe (WGI AR5 Section 14.6.2.2). Loss ratios—that is, insured loss divided by insured value—follow the same pattern (Schwierz et al., 2010; Donat et al., 2011; Pinto et al., 2012; see also Table 10-5). Return periods per loss level are projected to shorten in large parts of Europe, indicating more frequent high losses (Pinto et al., 2012; see Table 10-5). Projected overall losses and fatalities develop accordingly (Narita et al., 2010; IPCC, 2012). Across three modeling approaches calibrated to

Table 10-4 | Observed normalized insured losses from weather hazards (trends significant at the 10% level are indicated as a trend).

Region	Peril accounted for in normalized insured property losses	Observation period	Trend in insured losses—otherwise specified (aggregation mode)	Reference
World	All weather-related	1990–2008	No trend (annual aggregates)	1
Australia	Aggregate of bushfire, flood, hailstorm, thunderstorm, tropical cyclone	1967–2006	No trend (annual aggregates)	7
West Germany	All weather-related	1980–2008	Positive trend (annual aggregates)	1
	Winter storms			
	Floods	1980–2008	No trend (annual aggregates)	
	Convective events			
Southwest Germany	Hailstorm	1986–2004	Positive trends in annual frequency of days exceeding thresholds of daily damage claim counts Increase in annual count of hail damage claims	8
Spain	Floods	1971–2008	No trend (annual aggregates)	2
USA east of 109°W	Convective events (hail, heavy precipitation and flash flood, straight-line wind, tornado)	1970–2009 (March to September)	Standard deviation (variability) by a factor 1.65 greater for 1990–2009 than for 1970–1989 Mean annual loss by a factor 2.67 greater for 1990–2009 than for 1970–1989 Data: normalized insured loss exceeding US$150 million per event, annual aggregates	9
USA	Winter storms (ice storms, blizzards and snow storms)	1949–2003	Positive trend (pentade totals) Positive trend (average loss per state, pentade totals)	3
	All flood ("flood only" and floods specifically caused by convective storms, tropical cyclones, snow melt)	1972–2006	Positive trend (annual aggregates)	4
	Tropical cyclones	1949–2004	Increase (7-year totals) No statistical trend assessment.	5
	Hailstorm	1951–2006	Focus on top-ten major hailstorm losses of the period 1951–2006. Increase in frequency and loss in the 1992–2006 period as compared to 1951–1991. No statistical trend assessment	6
	All weather-related	1973–2008	Positive trend (annual aggregates)	1
	Floods			
	Convective events			
	Winter storms			
	Tropical cyclones			
	Heat episodes			
	Cold spells	1973–2008	No trend (annual aggregates)	

Sources: [1]Barthel and Neumayer (2012); [2]Barredo et al. (2012); [3]Changnon (2007); [4]Changnon (2008); [5]Changnon (2009a); [6]Changnon (2009b); [7]Crompton and McAneney (2008); [8]Kunz et al. (2009); [9]Sander et al. (2013).

Table 10-5 | Climate change projections of insured losses and/or insurance prices.

Hazard	Insurance line	Region	Projected changes in future time slices relative to current climate (spatial distribution and vulnerability of insured values assumed to be unchanged over time)
Winter storm	Homeowners' insurance	Europe	Projected increases in mean annual loss ratio lie in a range from one- to two-digit percentages in time slices before and around 2050 for regions such as France, Belgium/Netherlands, UK/Ireland, Germany, and Poland, with larger increases at the end of the century. Southern European regions expect decreases, such as Portugal/Spain (SRES A1B, A2).[4,5,8,13–15,19] Currently rare and high annual loss ratios are projected to occur more often: today's 20-year, 10-year, and 5-year return periods appear strongly reduced by the end of the century for individual countries. For entire Europe they will roughly be halved (SRES A2).[16] Accordingly, return periods will have higher loss levels associated,[10,19] e.g., the 25-year loss in Germany is expected to rise by 5–41% in 2041–2070 (SRES A1B).[8,10]
River flood, maritime flood, flash flood from rainfall, melting snow	Property and business interruption insurances	Europe, North America	Germany: projected increases in mean annual insured flood loss according to a seven-member dynamical downscaling ensemble mean (SRES B1, A1B, A2) are 84% (2011–2040), 91% (2041–2070), and 114% (2071–2100).[7] United Kingdom: projected increases in mean annual insured flood loss are 8% (for a +2°C rise in global mean temperature) and 14% (for a +4°C rise), with the one-in-hundred-year loss higher by 18% and 30%, respectively.[4] Norway, Canada: losses from heavy precipitation in property and business interruption insurances in three city areas in Canada are projected to rise by 13% (2016–2035), 20% (2046–2065), and 30% (2081–2100) in a five-member ensemble mean (IS92a, SRES A2/B2, A2)[3]. In three counties across southern Norway precipitation and snow melt insurance losses are expected to be higher by approximately 10–21% (SRES A2) and 17–32% (SRES B2) at the end of the century.[9] The Netherlands: expected annual property loss caused by increasing river discharge and sea level with an assumed flood insurance system is projected to lie by 125% higher in 2040 relative to 2015 (corresponding to 24 cm sea level rise) and by 1784% higher in 2100 (85 cm sea level rise).[1]
Tropical cyclone	Foremost property insurance lines	North America, Asia	USA: three of four GCMs driving a specific tropical cyclone and loss model entail increasing insured hurricane losses over time (SRES A1B).[6] Two GCM outputs at coarser resolution for the end of the century produce contradictory results of prolonged (ECHAM5/MPIOM A2) versus shortened (MRI/JMA A1B) return periods of current loss levels.[17] Analogously, a wide range of model projections is reflected in price levels of Florida's hurricane wind insurance that are projected to change by –20% to +5% (2020s) and –28% to +10% (2040s) (under the assumptions of strained reinsurance capacity, i.e., hard market conditions, and current adaptation).[12,18] These approaches demonstrate uncertainty in the sign of change. China: projected increases of insured typhoon losses are 20% (for a +2°C rise in global mean temperature) and 32% (for a +4°C scenario), with the one-in-hundred-year loss higher by 7% and 9%, respectively.[4]
Hailstorm	Homeowners' insurance, agricultural insurances	Europe	The Netherlands: losses from outdoor farming insurance and greenhouse horticulture insurance are projected to increase by 25–29% and 116–134%, respectively, for a +1°C rise in global mean temperature. For a +2°C scenario, projected increases will be higher at 49% to 58% and 219% to 269%, respectively (statistical model).[2] Germany: projected increases in mean annual loss ratios from homeowners' insurance due to hail are 15% (2011–2040) and 47% (2041–2070) (SRES A1B, statistical model).[8]
Storms, pests, diseases	Paddy rice insurance	Asia	Japan: paddy rice insurance payouts are projected to decrease by 13% by the 2070s, on the basis of changes in standard yield and yield loss (A2).[11]

Notes: GCM = General Circulation Model; ECHAM5 = European Centre for Medium Range Weather Forecasts and (Max Planck Institute of Meteorology) Hamburg, fifth GCM generation; MRI = Meteorological Research Institute of Japan Meteorological Agency (JMA); SRES = Special Report on Emission Scenarios.

Sources: [1]Aerts and Botzen (2011); [2]Botzen et al. (2010b); [3]Cheng et al. (2012); [4]Dailey et al. (2009); [5]Donat et al. (2011); [6]Emanuel (2011); [7]German Insurance Association (Gesamtverband der Deutschen Versicherungswirtschaft) (2011); [8]Gerstengarbe et al. (2013); [9]Haug et al. (2011); [10]Held et al. (2013); [11]Iizumi et al. (2008); [12]Kunreuther et al. (2012); [13]Leckebusch et al. (2007); [14]Pinto et al. (2007); [15]Pinto et al. (2009); [16]Pinto et al. (2012); [17]Raible et al. (2012); [18]Ranger and Niehoerster (2012); [19]Schwierz et al. (2010).

German insurance data, the 25-year loss is projected (SRES A1B) to change by –10% to +26% (2011–2040), +5% to +41% (2041–2070), and +45% to +58% (2071–2100) against 1971–2000, keeping exposures and damage sensitivities constant (Held et al., 2013). Although it is *unlikely* that the North Atlantic response to climate change is just a simple poleward shift of the storm track, overall confidence in the magnitude of regional storm track changes is low (WGI AR5 Section 14.6.3).

Direct losses and fatalities from flooding will increase with climate change in various locations in the absence of adequate adaptation, given *very likely* widespread increases in heavy precipitation (WGI AR5 Sections 11.3.2.5.2, 12.4.5.4; see also IPCC, 2012). This is selectively reflected in studies projecting mean annual insured heavy rainfall and flood losses to rise with climate change in the UK, the Netherlands, Germany, southern Norway, and the Canadian province of Ontario (Table 10-5).

Direct losses and fatalities from tropical cyclones will increase with exposure and may increase with the frequency of very intense cyclones in some basins (WGI AR5 Section 14.6; Nordhaus, 2010; IPCC, 2012; Peduzzi et al., 2012). Ranger and Niehoerster (2012), Kunreuther et al. (2012), and Raible et al. (2012) found insured hurricane losses change in opposite directions across a range of dynamical and statistical model projections, whereas a high-resolution approach tends to support a long-term increase (Emanuel, 2011). Here, increased probabilities of upward shifted accumulated loss might be detectable by 2025 at earliest, whereas a significant loss trend might emerge much later (Crompton et al., 2011; Emanuel, 2011).

Insured typhoon-related property losses in China are projected to increase (Dailey et al., 2009). Averaged across four GCMs, Mendelsohn et al. (2012) project rising direct losses for Central America, the Caribbean, North America, and East Asia. Narita et al. (2009) report an increase in damages and fatalities in all parts of the world.

Hailstorm insurance losses in the Netherlands (Botzen et al., 2010b) and Germany (Gerstengarbe et al., 2013) are projected to increase, consistent with more severe thunderstorms (WGI AR5 Section 12.4.5.5). Paddy rice insurance payouts in Japan are projected to decrease (Iizumi et al., 2008; see Table 10-5).

Rising insured wealth will increase both losses and premium income, not necessarily altering the ratio of both. Such automatic compensation is not effective for changing hazards. Hence, projected ratios of losses to premiums or sums insured (while assuming constant insured property) are an approximation of the climate change impact (Donat et al., 2011). Additional impact factors such as future economic growth (Aerts and Botzen, 2011) or changing vulnerability are rarely projected.

10.7.4. Fundamental Supply-Side Challenges and Sensitivities

10.7.4.1. High-Income Countries

The provision of weather hazard insurance is contingent on an insurer's ability to find a balance between affordability of the premiums and costs that have to be covered by the revenue. Costs include the expected level of losses, expenses for risk assessment, product development, marketing, operating, and claims processing. Moreover, the revenue must provide a return on shareholders' equity and allow for the purchase of external capital to cover large losses (Charpentier, 2008; Kunreuther et al., 2009).

The balance between affordability and profitability is sensitive to climate change. Increases in large weather-related losses may corrode an insurer's solvency if it fails to adjust its risk management, or is hampered in doing so by price regulation (Grace and Klein, 2009). In addition, misguided incentives for development in hazard-prone areas, as with the U.S. National Flood Insurance Program (Michel-Kerjan, 2010; Kousky and Kunreuther, 2010; GAO, 2011) can aggravate the situation (see Table 10-6).

The additional uncertainty induced by climate change translates into a need for more risk capital (Charpentier, 2008; Grace and Klein, 2009; Kunreuther et al., 2009). This raises insurance premiums and affects the economy (Table 10-6). Health and life insurance may also be affected through the health impacts of climate change (Hecht, 2008). Liability insurance, too, may be susceptible to climate change. So far, no damages have been awarded for greenhouse gas emissions as such, but litigation where damages are sought is pending (Heintz et al., 2009; Mills, 2009; Patton, 2011). Defense cost coverage under liability insurance in such cases depends on the specific contractual wording (Supreme Court of Virginia, USA, 2012; see Table 10-6).

10.7.4.2. Middle- and Low-Income Countries

Middle- and low-income countries account for a small share of worldwide non-life insurance: approximately 14% of premiums in 2012 (Swiss Re, 2013b). In high-income countries, some 37% of direct natural disaster losses have been covered by insurance in the period 1980–2011, about 4% in middle-income countries, and even less in low-income countries (Wirtz et al., 2013). For instance, only about 1% of direct overall losses in the 2010 floods in Pakistan were insured (Munich Re., 2011).

Table 10-6 | Fundamental supply-side challenges and sensitivities.

Challenges that might increase in the climate change context	Example/explanation
Failure to reflect temporal changes in hazard condition in risk management	After the devastating 2004 and 2005 hurricane seasons, the losses of Florida's homeowners' insurance accumulated since 1985 exceeded the cumulative direct premiums earned by 31%. Consequences of the upswing and peak in hurricane activity: one insurer liquidated, two seized by regulation due to insolvency; reduced coverage availability in high-risk areas.[9]
Misguided incentives additionally increasing risk	US National Flood Insurance Program (NFIP) allows for a vicious circle of built-up areas already existing within flood plains pressing authorities to construct or improve protecting levees that in turn lead to even more development attracted by NFIP premium discounts, although exposed to extreme flooding events.[11,22] In addition, the large majority of older properties situated within flood plains and accounting for 16% of losses in the period 1978–2008 pay premiums substantially below the risk-adequate level.[14; see also 1,6,7,11,15] In this respect, premium incentives to reduce residual flood risk have been missing. Policyholders residing in flood plains where flood cover was made precondition for mortgage drop the cover after only 2–4 years, accounting for missing insurance penetration and insufficient build-up of NFIP risk capital.[11,14,15] All these features, among others, account for the fact that NFIP has continuously been running a cumulative operating deficit, reaching more than US$20 billion in 2006, after the big hurricanes.[14]
Non-quantifiable uncertainties increasing risk	There is ambiguity as to what degree climate change may modify regional weather hazards—model projections are not unequivocal,[2,3] and there is uncertainty about prospects of post-disaster regulatory/jurisdictional pressures, e.g., to extend claims payments beyond the original coverage.[9] Such uncertainties materialize in risk-based capital loadings.[12]
Liability insurance impacted by new climate risk	Chances of success for claims based on CO_2 emissions in the USA seem small, owing to legal obstacles,[4,5,8,18] even though allocation schemes to overcome these hurdles are being discussed.[17,20] Defense costs could be covered by liability insurance.[20] CO_2 emissions were declared pollution (US Supreme Court/EPA). Existing and future regulation on limits for CO_2 emissions could continue to displace liability claims for CO_2 emissions and at the same time create new liability risks in case of non-compliance. These risks have not yet been adequately taken into account, somewhat similar to the early stages of environmental liability claims in the USA in the 20th century.[10,16] The Supreme Court of Virginia ruled in 2012 that coverage under liability insurance for claims based on CO_2 emissions and defense costs depends on the specific occurrence-definition underlying the contract (e.g., if the cover pertains to accident, warming due to CO_2 emissions and resulting damage does not match this definition).[19]
Share of insurance in national risk financing	In the years following weather-related disasters countries with high insurance penetration show almost no impact on sovereign deficit and increasing economic output (GDP), whereas low-penetration countries experience substantially rising government deficit and missing positive change in output.[13,21] The absence of developed insurance systems, as is the case in many middle- and low-income countries, translates into greater macroeconomic vulnerability than with developed insurance systems.

Sources: [1]Burby (2006); [2]Charpentier (2008); [3]Collier et al. (2009); [4]Ebert (2010); [5]Faure and Peeters (2011); [6]GAO (2010); [7]GAO (2011); [8]Gerrard (2007); [9]Grace and Klein (2009); [10]Hecht (2008); [11]Kousky and Kunreuther (2010); [12]Kunreuther et al. (2009); [13]Melecky and Raddatz (2011); [14]Michel-Kerjan (2010); [15]Michel-Kerjan and Kunreuther (2011); [16]Mills (2009); [17]Patton (2011); [18]Stewart and Willard (2010); [19]Supreme Court of Virginia USA (2012); [20]Taylor and Tollin (2009); [21]von Peter et al. (2012); [22]Zahran et al. (2009).

The small share of insurance in risk financing in middle- and low-income countries may be insufficient because other options, such as external credit or donor assistance, can be unreliable and late. This leaves a financial gap in the months immediately following an EWE, often exacerbated by overstretched public finances. Pre-disaster financing instruments such as insurance or trigger-based risk-transfer products have proven to be effective means of providing prompt liquidity for households, businesses, and governments (Ghesquiere and Mahul, 2007; Linnerooth-Bayer et al., 2011; Melecky and Raddatz, 2011; IPCC, 2012; von Peter et al., 2012; see Table 10-6). These may become more important if disaster incidence increases with climate change (Collier et al., 2009; Hochrainer et al., 2010; IPCC, 2012).

It is challenging to increase catastrophe insurance coverage because of low business volumes, high transaction costs, and high reinsurance premiums following large disasters. Small-scale insurance schemes in middle- and low-income countries may find it difficult to obtain sufficient risk capital (Cummins and Mahul, 2009; Mahul and Stutley, 2010).

Microinsurance schemes, keeping transaction costs at the lowest operable level, mainly provide health and life insurance to households and small enterprises in low-income markets. Supply of property insurance suffers from correlated weather risks, although weather-related agricultural damages are covered. Such weather coverage is growing, typically with government and non-governmental organization (NGO) assistance or cross-subsidies from local insurers (Linnerooth-Bayer et al., 2011; Qureshi and Reinhard, 2011). These schemes may be particularly sensitive to a rise in disaster risk due to climate change (Collier et al., 2009; Leblois and Quirion, 2011; Clarke and Grenham, 2012).

Adverse selection is another challenge: clients do not always disclose their true risk, for example, a floodplain site, to the insurer so as to benefit from lower rates. Lower-risk participants may be charged too high premiums and leave the scheme, thus increasing overall risk; and in low-income countries, where data to establish homogeneous risk groups are not available, this can cause disaster insurance markets to fail. Moral hazard is another issue, where the insured adopt more risky behavior than anticipated by the insurer, particularly in the absence of proper monitoring (Barnett et al., 2008; Mahul and Stutley, 2010).

10.7.5. Products and Systems Responding to Changes in Weather Risks

10.7.5.1. High-Income Countries

A rise in weather-related disaster risk may drive the need for more risk-based capital to cover the losses. There are several options that sustain insurability. Reducing vulnerability often makes sense even if expected climate change impacts will not materialize. Theoretically, risk-based premiums incentivize policyholders to reduce their vulnerability (Hecht, 2008; Kunreuther et al., 2009; IPCC, 2012; see Table 10-7). Premium discounts for loss prevention can further promote this (Ward et al., 2008; Kunreuther et al., 2009; see Table 10-7). Moral hazard can be reduced by involving the policyholder in the payment of losses, for example, via deductibles or upper limits of insurance coverage (Botzen and van den Bergh, 2009; Botzen et al., 2009). Coordinated efforts of insurers and governments on damage prevention decrease risk (Ward et al., 2008; Reinhold et al., 2012). For example, new building standards in Florida reduced mean damage per house by 42% in the period 1996–2004 relative to pre-1996; risks can be further reduced, and premium discounts contingent on building standard are offered (Kunreuther et al., 2009, 2012). However, risk-based premiums required to incentivize vulnerability reduction are often hampered (see also Sections 15.4.4, 17.5.1). Price regulation, subsidies, competitive pressures, and bundling of perils in one product (implying cross-subsidies) have fostered underpricing. Also, availability of sufficient on-site risk information limits price adequacy, for example, for flood insurance (Maynard and Ranger, 2012).

Most commercial risk-assessment models only incipiently factor in changes in weather hazards, mainly to reflect higher hurricane frequencies (Seo and Mahul, 2009), assuming unchanging conditions for other weather hazards. Ignoring changing hazard conditions results in biased estimates of expected loss, loss variability, and risk capital requirements (Charpentier, 2008; Herweijer et al., 2009; see also Section 10.7.3). Other confounding factors, for example, systemic economic impact, in recent large losses have been addressed (Muir-Wood and Grossi, 2008; see Table 10-7). Geospatial risk-assessment tools, such as flood-recurrence zoning with premium differentiation, counteract adverse selection (Kunreuther et al., 2009; Mahul and Stutley, 2010). Some insurers have offered weather alert systems to clients (Niesing, 2004). Further, credit rating agencies and Solvency II insurance regulations in Europe contribute to enhanced disaster resilience (Michel-Kerjan and Morlaye, 2008; Grace and Klein, 2009; Kunreuther et al., 2009). Finally, insurers and researchers have projected climate change-driven losses to allow for adaptation of the industry (Section 10.7.3).

Reinsurers are key to the supply of disaster risk capital. They operate globally to diversify the regional risks of hurricanes and other disasters. Access to reinsurance enhances risk diversification of insurers. Periodic shortages in reinsurance capacity following major disasters have moderated over the last 2 decades because of easier new capital inflow (Cummins and Mahul, 2009).

Global diversification potential of large losses has fallen over recent decades because of increasing dependence between major insurance markets. For instance, the floods in Thailand in 2011 disrupted industrial hubs and global supply chains (Courbage et al., 2012). This process may continue with climate change (Sherement and Lucas, 2009; Kousky and Cooke, 2012). However, global diversification potential can be increased by developing insurance markets in middle- and low-income countries (Cummins and Mahul, 2009).

Very large loss events, say in excess of US$100 billion, may make additional capacity desirable. These disasters can be diversified in the financial securitization market (IPCC, 2012). Natural catastrophe risks do not correlate with capital market risks and hence are attractive to institutional investors. For instance, a catastrophe bond assures the investor above-market returns as long as a parametric index (e.g., wind-based) does not exceed a threshold, but pays the insurer's loss otherwise. The catastrophe bond market reached critical mass after the hurricanes of 2004 and 2005, with some US$11 billion of risk capital in effect by June 2011 (Michel-Kerjan and Morlaye, 2008; Cummins and Weiss, 2009; see Table 10-7).

Table 10-7 | Products and systems responding to changes in weather risks.

Response option	Example/explanation
Risk-adjusted premiums convey the risk to the insured, encouraging them to pursue adaptive measures.	Flood hazard insurance zoning systems, e.g., HORA (Austria), SIGRA (Italy), and ZÜRS (Germany), hamper development in high-risk zones by allocating adequately high premiums.[26] Prior to Germany's disastrous River Elbe flood in 2002, 48.5% of insured households had obtained information on flood mitigation or were involved in emergency networks and 28.5% implemented one of several mitigation measures compared with 33.9% and 20.5%, respectively, of uninsured households.[42] However, perceptions that motivate flood insurance uptake range from risk awareness[9] to pure peer group expectation[32]—the latter might blur the role of the risk-premiums-nexus in some societal contexts.
Conditions of insurance policies incentivizing vulnerability reduction	Premium discounts for compliance with local building codes or other prevention options[27,45]; share of the insured in claims payment by deductibles or upper coverage limits, and exclusion of systematically affected property[1,7,8,10,11,15,21]; long-term natural-hazard insurance tied to the property and linked to mortgages and loans granted for prevention measures.[27,28,36] The latter is contested by modeled high-risk capital requirements and ambiguity loadings, rendering multi-year policies relatively expensive and less flexible for the insurance market.[34]
Amplifying factors in large disaster losses included in risk models	Evacuation and systemic economic catastrophe impacts, adversely affecting regional workforce and repair capacity, or knock-on catastrophes following initial catastrophes, e.g., long-term flooding following hurricane landfall.[38]
Diversifying large disaster risk across securitization markets	Following the hurricane disasters of 2004 and 2005, securitization instruments, e.g., catastrophe bonds, industry loss warranties, and sidecars, acquired greater prominence, and have been recovering again from the market break in 2008.[16,18,20] Investors in insurance linked securities are attracted by the lack of correlation to typical financial market risks (e.g., currency risks) and the well defined loss-per-index structure. The higher transparency relative to other asset-backed securities, such as mortgage-backed securities, contributed to the better performance of catastrophe bonds following the financial crisis of 2007/2008.[16,18] As bonds typically cover large losses, the basis risk, i.e., suffering damage without parametric triggering, is reduced[44]; further reduction may be feasible by optimizing index measurements.[16] Weather derivatives are further instruments used to transfer risks to the capital markets.[17,27,37] Also, multiple-trigger "hybrid" products are available, combining a parametric trigger-based catastrophe bond with a trigger-based protection against a simultaneous drop in stock market prices, thereby hedging against a double hit from direct disaster loss and losses incurred by the asset management side.[5,18]
Index-based weather crop insurance products	Agricultural insurances predominantly cover crops, but also livestock, forestry, aquaculture, and greenhouses. Main products are indemnity-based crop insurance (covers for single perils and multiple-peril events), and index-based crop insurance.[41] The latter is available in 40% of middle-income countries, with enlarged systems beyond pilot implementation in India and Mexico, and growth in China.[23,33,40,46] Risk-based price signals may better foster adaptation if schemes are coupled with access to advanced technology, e.g., drought-resistant seed.[4,15,23,33] Various index definitions (cumulative rainfall, area-yield, etc.) and applications exist or have been proposed.[4,29,30,31] Adjusting to uncertain regional changes in temporal hazard condition is a basic challenge with climate change.[14,24,29]
Improvements in index-based weather insurance	Basis risk, i.e., weak correlation between index and damage, can be reduced if the index scheme is applied to an area-yield trigger in a region with homogeneous production potential (e.g., based on a sample) and/or to the uppermost disaster risk layer only.[14,15,22] It can be better absorbed if index insurance works at aggregate level, e.g., to cover crop-credit portfolios, cooperatives, or informal networks,[43] and if satellite-based remote-sensing technology can be used to establish plot identification and yield estimation and loss assessment.[22] Satellite-based forage estimation is already used for livestock index insurance in East Africa.[13] Pooling local schemes across climate regions under one cooperative parent organization, thus realizing central management, economics of scale, and risk diversification, can reduce capital requirements and advance performance.[6,12,35] The disaster risk layer and high start-up costs (weather data collection, risk modeling, education) necessitate subsidies from the state or donors.[15,33]
Sovereign insurance schemes	Economic theory about the public sector's risk neutrality argues (1) that risks borne publicly render the social cost of risk-bearing insignificant and (2) that disaster loss is seen small in comparison with a government's portfolio of diversified assets.[3] This theory proved inadequate if applied to relatively vulnerable small-sized middle- to low-income countries,[19] thereby rehabilitating sovereign insurance. For the Caribbean scheme CCRIF, which pools states, the reduction in premium cost per country is expected to be 45–50%.[31] Similar pooling schemes are being developed (e.g., African Risk Capacity, Pacific Catastrophe Risk Insurance Pilot).[2,39] Pooling natural catastrophe risks across an array of megacities has also been proposed.[25]

Sources: [1]Aakre et al. (2010); [2]Wilcox et al. (2010); [3]Arrow and Lind (1970); [4]Barnett et al. (2008); [5]Barrieu and Loubergé (2009); [6]Biener and Eling (2012); [7]Botzen and van den Bergh (2008); [8]Botzen and van den Bergh (2009); [9]Botzen and van den Bergh (2012); [10]Botzen et al. (2009); [11]Botzen et al. (2010a); [12]Candel (2007); [13]Chantarat et al. (2013); [14]Clarke and Grenham (2012); [15]Collier et al. (2009); [16]Cummins (2012); [17]Cummins and Mahul (2009); [18]Cummins and Weiss (2009); [19]Ghesquiere and Mahul (2007); [20]Guy Carpenter (2011); [21]Hecht (2008); [22]Herbold (2013b); [23]Hess and Hazell (2009); [24]Hochrainer et al. (2010); [25]Hochrainer and Mechler (2011); [26]Kron (2009); [27]Kunreuther et al. (2009); [28]Kunreuther and Michel-Kerjan (2009); [29]Leblois and Quirion (2011); [30]Leiva and Skees (2008); [31]Linnerooth-Bayer and Mechler (2009); [32]Lo (2013); [33]Mahul and Stutley (2010); [34]Maynard and Ranger (2012); [35]Meze-Hausken et al. (2009); [36]Michel-Kerjan and Kunreuther (2011); [37]Michel-Kerjan and Morlaye (2008); [38]Muir-Wood and Grossi (2008); [39]The World Bank (2013); [40]Prabhakar et al. (2013); [41]Swiss Re (2013a); [42]Thieken et al. (2006); [43]Trærup (2012); [44]Van Nostrand and Nevius (2011); [45]Ward et al. (2008); [46]Zhu (2011).

10.7.5.2. Middle- and Low-Income Countries

Index-based weather insurance is often considered well-suited to the agricultural sector in developing countries (Collier et al., 2009; IPCC, 2012). Payouts depend on a physical trigger, for example, cumulative rainfall at a nearby weather station, instead of the policyholder's condition. Thus, they can be timely; costly loss assessments and moral hazard are avoided; and adverse selection reduced (Barnett et al., 2008). Risk-based premiums can encourage adaptive responses (Mahul and Stutley, 2010; see Table 10-7). However, basis risk, where losses occur but no payout is triggered, provokes distrust. Misunderstanding and scaling up of pilots pose further difficulties (Patt et al., 2010; Leblois and Quirion, 2011; Clarke and Grenham, 2012). Suggested improvements include area-yield indices and coverage at aggregate levels to reduce basis risk, and a cooperative design (Biener and Eling, 2012; Clarke and Grenham, 2012; see Table 10-7). Application of indemnity-based insurance and index-based concepts depend on the insured's characteristics and the market setting (Herbold, 2013a; Swiss Re, 2013a). Insurance-linked services can strengthen farmers' resilience by seasonal-forecast-based agricultural guidance (AgroClima, 2013).

Improved building standards at high-risk sites in the Caribbean substantially reduce damages from tropical cyclones and increase benefits twofold over costs over a 20-year period, assuming scenarios of changing hazard inferred from past decades (Michel-Kerjan et al., 2013; Ou-Yang et al., 2013). Insurance coverage linked to credit for retrofitting could improve adaptation (Mechler et al., 2006).

Sovereign insurance is deemed appropriate in developing countries suffering from post-disaster financing gaps (see Section 10.7.4). Current schemes include government disaster reserve funds (FONDEN, Mexico) and pools of developing states' sovereign risks (e.g., CCRIF, Caribbean;

IPCC, 2012). In both cases, peak risk is transferred to reinsurance and catastrophe bonds (Table 10-7).

10.7.6. Governance, Public–Private Partnerships, and Insurance Market Regulation

10.7.6.1. High-Income Countries

Theory favors an arrangement where individual risk is insured, but the non-diversifiable component of risk (that may rise with climate change) is public (Borch, 1962; Kunreuther et al., 2009). Accordingly, many high-income states have public-private arrangements involving government intervention on peak risk (Aakre et al., 2010; Bruggeman et al., 2010; Schwarze et al., 2011; Paudel, 2012), or even public statutory insurance systems (Quinto, 2011; see Table 10-8). Expected governmental post-disaster relief has been shown to counteract insurance uptake (Raschky et al., 2013). The pro-adaptive, risk-reducing features of insurance are more effective if the price reflects the risk and the pool of insureds is larger, for example, through bundled perils (Bruggeman et al., 2010; Paudel, 2012). People who cannot afford premiums can be covered by vouchers, leaving the price signal undistorted, or by subsidies (Kunreuther et al., 2009; Aakre et al., 2010; see Table 10-8).

Insurance regulation ensures availability, affordability, and solvency, but often adopts only short- to medium-term views. Because of climate change, the role of regulators has changed to include risk-adequate pricing, risk education, and risk-reduction in the long term (Hecht, 2008; Grace and Klein, 2009; Mills, 2009).

10.7.6.2. Middle- and Low-Income Countries

A key element of risk financing is the transfer of private risks to an insurance system. This reduces the governments' burden and uncertainty due to weather disasters (Ghesquiere and Mahul, 2007; Melecky and Raddatz, 2011). Interest in public-private partnerships may evolve, for example, between government, farmers, rural banks, and insurers, in order to expedite agricultural development and resilience, for example, by means of subsidies for start-up costs and peak risk (Collier et al., 2009; Mahul and Stutley, 2010; see Table 10-8). Previously implemented systems have suffered from adverse selection and moral hazard (Makki and Somwaru, 2001; Glauber, 2004), suggesting an improved design is needed. For instance, group policies foster mutual monitoring. Programs or legislative actions that encourage purchase of insurance may increase participation rates. Further, insurance pools can diversify weather risks across larger regions, reduce premiums, and improve access to external risk capital (Mendoza, 2009; Hochrainer and Mechler, 2011; Biener and Eling, 2012; IPCC, 2012).

In least developed countries, domestic insurance markets are rare. Climate change-related disaster risk management was proposed for inclusion in the adaptation regime of the United Nations Framework Convention on Climate Change (UNFCCC). Besides prevention, insurance is a central element in these concepts, partly funded from a UNFCCC adaptation fund according to the principles of "equity and […] common but differentiated responsibilities and respective capabilities" (UNFCCC Art. 3.1; Linnerooth-Bayer et al., 2009; Warner and Spiegel, 2009; IPCC, 2012; see Table 10-8).

For insurance systems in developing markets, challenges include adequate public-private partnership framing, improved risk assessment with sufficient detail and appropriate dynamics, development of markets and regulation, and scaling-up of successful schemes. Regulatory requirements for risk-based capital, and access to reinsurance and securitization markets, further contribute to a resilient insurance system.

10.7.7. Financial Services

The financial industry apart from insurance is vulnerable to both slow-onset changes and to more frequent and/or intensive weather-related disasters. Equity investors potentially face a higher exposure than debt investors, due to exit conditions and a focus on longer-term returns in equity markets, but ultimately the impact on debt investors depends on the exposure of credit collateral to climate change (Stenek et al., 2010). In the short- to medium-term, the financial sector is better sheltered from climate change due to high capital mobility, an ability to hedge

Table 10-8 | Governance, public–private partnerships, and insurance market regulation.

Structural element	Example/explanation
Public–private arrangements involving government intervention on the non-diversifiable disaster risk portion	Systems with government intervention range from ex ante risk financing design, such as public monopoly natural hazard insurance (e.g., Switzerland, with inter-cantonal pool) or compulsory forms of coverage to maximize the pool of insureds (e.g., Spain, France, with unlimited state guarantee on top), to ex post financing design, such as taxation-based governmental relief funds (e.g., Austria, Netherlands). In between these boundaries rank predominantly private insurance markets, in several countries combined with governmental post-disaster ad hoc relief (e.g., Germany, Italy, UK, Poland, USA)[13]; see also [1,3,4,10,11,12,14].
Care for people who cannot afford insurance	Either by funds outside the insurance system, e.g., insurance vouchers, or by premium subsidies (particularly for the catastrophic risk portion).[1,6,14]
Public-private partnership to expedite agricultural development	Insurance improves the farmers' creditworthiness, which in turn strengthens their adaptive capacity. For instance, by means of loans farmers can step from low-yield to higher-yield cropping systems.[2,8,9]
Concepts for adaptation-oriented climate change risk management frameworks linked to United Nations Framework Convention on Climate Change (UNFCCC)	Risk prevention and risk reduction often are the starting points that can absorb many of the smaller weather risks, and various forms of insurance, including international coordination, are meant to cover all of the remaining risks.[7,15,16] A global framework, where the wealthy agree to pool risks with the most vulnerable, equals social insurance that is different from a risk-based share in insurance funds.[5]

Sources: [1]Aakre et al. (2010); [2]Barnett et al. (2008); [3]Botzen and van den Bergh (2008); [4]Bruggeman et al. (2010); [5]Duus-Otterström and Jagers (2011); [6]Kunreuther et al. (2009); [7]Linnerooth-Bayer et al (2009); [8]Linnerooth-Bayer et al. (2011); [9]Mahul and Stutley (2010); [10]Monti (2012); [11]Paudel (2012); [12]Schwarze and Wagner (2007); [13]Schwarze et al. (2011); [14]Van den Berg and Faure (2006); [15]Warner and Spiegel (2009); [16]Warner et al (2012).

against a range of business risks, and an aptitude for the development of new products to cater for changing demand in particular with respect to risk transfers and investment in growing markets (Oliver Wyman, 2007; Whalley and Yuan, 2009). In the longer-term, some risks associated with climate change will be more difficult to diversify in particular for financial institutions with local reach.

There are few papers on the impact of climate change on the financial sector (other than insurance). Surveys agree with earlier views (WGII AR3 Section 8.4) that climate change is perceived as a material threat by few bankers and asset managers. There is growing awareness of climate change impacts, as illustrated by increasing membership of sector initiatives—such as the Carbon Disclosure Project, the UN Principles for Responsible Investment, or the Global Reporting Initiative—potentially influencing the responsiveness of the sector to climate change (Brimble and Stewart, 2009). However, only a few financial institutions have systematically factored in climate change into their risk management and analytical framework (Cogan et al., 2008; Furrer et al., 2012).

While direct physical impact (i.e., damage to financial infrastructure) is not seen to be a material issue, this may change in the future in light of the exposure of major financial centers to rising sea levels and the reliance on complex IT infrastructure. Moreover, there is an increasing share of equity allocated to infrastructure and real estate that is more long-term oriented and could face higher maintenance and adaptation requirements (Stenek et al., 2010; Mercer, 2011).

Indirect impacts may become material over the next few decades, for example, value losses of assets/loan portfolios as a result of physical damage. Regulatory and reputational effects, together with liability and litigation risks linked to climate change are of concern too (Cogan et al., 2008; Mercer, 2011; Furrer et al., 2012). However, legitimacy concerns linked to climate change (as reflected by clients) are insufficient, overshadowed by the financial crisis, or mitigated by the size and influence of the financial sector (Brimble and Stewart, 2009).

It is difficult to quantify how significant the impact of climate change will be for the industry. While it is not probable that climate change alone will affect the liquidity or financial capacity of an institution, the financial performance of both equity and debt markets could be weakened by a variety of factors including changes in market conditions through climate-driven price variations, higher capital and operating expenditure, or aggravation of country risk but also regulatory drivers, for example, higher capital reserve requirements to cover higher on- and off-balance-sheet exposures (Stenek et al., 2010).

10.7.8. Summary

More frequent or more severe extreme weather events, and increased uncertainty about such hazards, would lead to higher insurance premiums and reduced cover in several regions, to the detriment of the insured, and perhaps to reduced profitability of insurers, and to the detriment of their shareholders. Improvements in risk management, product innovation, financial innovation, and better regulation would partially alleviate these impacts.

10.8. Services Other than Tourism and Insurance

Other service sectors of the economy include waste management, wholesale and retail trade, engineering, government, education, defense, and health. Contributions to the economy vary substantially by country; however, overall worldwide economic activity related to government accounts for approximately 30% of global expenditures.

10.8.1. Sectors Other than Health

The literature on the impact of climate change on other sectors of the economy is sparse (see Section SM10.1 of the on-line supplementary material). Few studies have evaluated the possible impacts of climate change, and particularly the economic impacts, on these sectors. Tamiotti et al. (2009) conducted a qualitative assessment of climate and trade. Travers and Payne (1998) and Subak et al. (2000) find that weather affects retail, mostly through transfers in the economy. Sabbioni et al. (2009) note that climate change may require a greater effort to protect cultural heritage. Chapter 12 discusses the impact of climate change on violent conflict, which has implications for military expenditures.

10.8.2. Health

Climate change-related alterations in weather patterns, particularly extreme weather and climate events, have the potential to affect the health sector through impacts on infrastructure and the delivery of health care services from changing demand. Increased demands for services put additional burdens on public health and health care personnel and supplies, with potential economic consequences. For example, hydrologic disasters (floods and wet mass movements) in 2011 were associated with 20% of all reported disaster deaths and 19% of total damages (Guha-Sapir et al., 2012).

Health care facilities are priority infrastructure that can be damaged by weather and climate events, compromising critical resources required for patient treatment; physical damage and destruction of equipment and buildings; and possibly requiring evacuation of critical care patients, with attendant risks for the patients (Carthey et al., 2009). Adverse impacts on transportation (such as flooded roads) can further affect access and evacuation. The ability of health care facilities to properly care for the affected and for those with ongoing health issues requiring medication or treatment may be compromised by very large events that affect multiple health care facilities. Areas projected to experience increases in extreme events could consider additional "surge capacity" to manage such events without interruption of service (Banks et al., 2007; Hess et al., 2009).

Although the proportion of individuals seeking medical treatment during a disaster is typically a small subset of the total number of those affected, the additional burden on health care facilities can be significant (Hess et al., 2009). Six weather and climate events that struck the USA between 2000 and 2009 were estimated to have increased health care costs by US$740 million, reflecting more than 760,000 encounters with the health care system (Knowlton et al., 2011). Hospitalizations, with attendant costs, can increase from cases of heat stress, heat stroke, and

Frequently Asked Questions

FAQ 10.3 | Are other economic sectors vulnerable to climate change too?

Economic activities such as agriculture, forestry, fisheries, and mining are exposed to the weather and thus vulnerable to climate change. Other economic activities, such as manufacturing and services, largely take place in controlled environments and are not really exposed to climate change. However, markets connect sectors so that the impacts of climate change spill over from one activity to all others. The impact of climate change on economic development and growth also affects all sectors.

acerbations of cardiorespiratory diseases and other health conditions during heat waves (e.g., Lin et al., 2012; Astrom et al., 2013), and from the adverse health impacts of other extreme events (Sections 11.4.1-2). For example, one trauma center in the USA found a 5% increase in hourly admissions for each approximately 5°C increase in temperature (Rising et al., 2006). Individuals looking for an air-conditioned location during high ambient temperatures can further increase hospital visits (Carthey et al., 2009).

Climate change is projected to increase the burden of major worldwide causes of childhood mortality, including malnutrition, diarrheal diseases, and malaria (Sections 11.5.1-2, 11.6.1). Any increase in health burdens or risks would increase the demands for public health services (e.g., surveillance and control programs) and the demands for health care and relevant supplies (e.g., antimalarials, insecticide-treated bednets, oral rehydration). Studies estimating the costs of additional cases of climate-sensitive health outcomes focus on the costs of treatment, typically omitting the costs of providing additional health services, implementing new policies, and health actions in other sectors (Hutton, 2011). Because most climate change-related cases of adverse health outcomes are projected to occur in low-income countries, treatment costs will primarily be borne by families where governments provide limited health care (WHO, 2004). Time off from work to care for sick children could affect productivity.

Public and private health expenditures account for approximately 10% of global GDP (http://data.worldbank.org/indicator/SH.XPD.TOTL.ZS). A systematic analysis of developing country government expenditures on health from domestic sources estimated that from 1995 to 2006, public financing of health in constant US$ increased nearly 100%; this was a product of rising GDP, slight decreases in the share of GDP spent by government, and increases in the share of government spending on health (Lu et al., 2010). The results varied by region, with shares of government expenditures on health increasing in many regions but decreasing in many sub-Saharan African countries. Development assistance for health rose from about US$8 billion (in constant US^{2007}) in 1995 to nearly US$19 billion in 2005 (Ravishankar et al., 2009). Domestic government spending on health was negatively affected by development assistance to governments and positively affected when assistance was to the non-governmental sector (Lu et al., 2010).

Estimates of the costs of treating future cases of adverse health outcomes from climate change are in the range of billions of US$ annually (Ebi, 2008; Pandey, 2010). An estimate of the worldwide costs in 2030 of additional cases of malnutrition, diarrheal disease, and malaria due to climate change—assuming no population or economic growth, emissions reductions resulting in stabilization at 750 ppm CO_2-eq in 2210, and current costs of treatment in developing countries—estimated treatment costs without adaptation could be US$4 to 12 billion worldwide, depending on assumptions of the sensitivity of these health outcomes to climate change (Ebi, 2008). The costs for additional infrastructure and health care workers were not estimated, nor were the costs of additional public health services, such as surveillance and monitoring. The costs were estimated to be unevenly distributed, with most of the costs borne by developing countries, particularly in Southeast Asia and Africa, to address the projected approximately 3 to 5% increase in the number of cases of diarrheal disease and malaria from the 2002 baseline (Markandya and Chaibai, 2009). The prevalence of these diseases have since declined (http://apps.who.int/gho/data/node.main.14?lang=en; Section 11.1.1), although there is considerable uncertainty in mortality data from many low-income countries because of the low proportion of deaths covered by vital registration programs (Byass et al., 2013).

A second global estimate assumed UN population projections, strong economic growth, updated projections of the current health burden of diarrheal diseases and malaria, two climate scenarios, and updated estimates of the costs of malaria treatment (Pandey, 2010). In 2010, the average annual adaptation costs for treating diarrheal disease and malaria were estimated to be US$3 to 5 billion, with the costs expected to decline over time with improvement in basic health services. Over the period 2010–2050, the average annual costs were estimated to be around US$2 billion, with most of the costs related to treating diarrheal disease; the largest burden is expected to be in sub-Saharan Africa. The differences in costs from Ebi (2008) are due primarily to a reduction in the baseline burden of disease and lower costs for malaria treatment.

Watkiss and Hunt (2012) estimated the health impacts of climate change in Europe in 2071–2100 using physical and monetary metrics, taking socioeconomic change into consideration. Temperature-related mortality during winter and summer due to climate change included positive and negative effects, with welfare costs (and benefits) of up to US$130 billion annually, with impacts unevenly distributed across countries. Assumptions about acclimatization influenced the size of the health impacts. The welfare costs for salmonellosis were estimated at potentially several hundred million euro annually, and those for the mental health impacts associated with coastal flooding due to climate change were up to approximately US$2 billion annually.

Estimated additional health care costs for climate change-related cases of malaria are similar in southern Africa (van Rensburg and Blignaut, 2002). Ranges for (low-high) additional cost scenarios for the prevention and treatment of malaria in South Africa in 2025 were estimated to be approximately US$280 to 3764 million. Estimates for Botswana and Namibia are US$9 to 124 million and US$13 to 177 million, respectively. The high cost scenario for Namibia is about 4.6% of GDP. The climate change-related malaria inpatient and outpatient treatments costs at the end of the century (2080–2100) in 25 African countries[1] indicated that even marginal changes in temperature and precipitation could affect the number of malaria cases, with increases in most countries and decreases in others (Egbendewe-Mondzozo et al., 2011). The end of century treatment costs as a proportion of annual 2000 health expenditures per 1000 people would increase in the vast majority of countries, with increases of more than 20% in inpatient treatment costs for Burundi, Côte D'Ivoire, Malawi, Rwanda, and Sudan.

The costs of treating cases of cholera in Tanzania due to climate change in 2030 were estimated to be in the range of 0.32 to 1.4% of GDP (Trærup et al., 2011), and there would be costs for treating additional cases of diarrhea and malaria in India in 2030, depending on the emission scenario (Ramakrishnan, 2011).

Bosello et al. (2006) used a computable general equilibrium model to study the economic impacts of climate-change-induced changes in mortality and morbidity due to cardiovascular and respiratory diseases, malaria, diarrhea, schistosomiasis, and dengue fever. They considered the effects on labor productivity and demand for health care, and found that health and welfare impacts have the same sign. The economy-wide health impacts were greater than simple aggregation of the costs of the individual health outcomes. Increased health problems were associated with an expansion of the public sector at the expense of the private sector.

Estimates of the impacts of climate change on worker productivity, assuming current work practices, primarily through heat stress, indicate that productivity has already declined during the hottest and wettest seasons in parts of Africa and Asia, with more than half of afternoon hours projected to be lost to the need for rest breaks in 2050 in Southeast Asia and up to a 20% loss in global productivity in 2100 under RCP4.5 (Kjellstrom et al., 2009, 2013; Dunne et al., 2013; see also Section 11.6.2). Alternate work practices may offer some relief from a health perspective, but would likely lead to significantly decreased productivity (Chapter 11).

10.9. Impacts on Markets and Development

Prior sections of this chapter present the direct impacts of climate change on the economy sector by sector. There are, however, also indirect impacts, from the one sector on the rest of the economy (Section 10.9.1) and on economic growth and development (Section 10.9.2).

[1] Algeria, Benin, Botswana, Burkina, Burundi, Central African Republic, Chad, Côte D'Ivoire, Djibouti, Egypt, Ethiopia, Ghana, Guinea, Malawi, Mali, Mauritania, Morocco, Niger, Rwanda, South Africa, Sudan, Togo, Uganda, Tanzania, Zimbabwe.

10.9.1. Effects of Markets

There are three channels through which economic impact diffuse. First, outputs of one sector are used as inputs to other sectors. For example, a change in crop yields would affect the food-processing industry. Second, products compete for the consumers' finite budget. If, for example, food becomes more expensive, a consumer would shift to cheaper food but also spend less money on other goods and services. Third, sectors compete for the primary factors of production (labor, capital, land, water). If, besides more fertilizers and irrigation, more labor is needed in agriculture to offset a drop in crop yields, less labor is available to produce other goods and services. Firms and households react to changes in relative prices, domestically and internationally. Ignoring these effects would lead to biased estimates of the impacts of climate change.

General equilibrium analysis describes how climate change impacts in one sector propagate to the rest of the economy, how impacts in one country influence other countries, and how macroeconomic conditions affect each impact (Ginsburgh and Keyzer, 1997). General equilibrium models can provide a comprehensive and internally consistent analysis of the medium-term impact of climate change on economic activity and welfare. However, these models necessarily make a number of simplifying assumptions, particularly with regard to the rationality of consumers and producers and the absence of market imperfections. Other types of economic models have yet to be applied to the estimation of indirect economic effects of climate change.

Computable general equilibrium models have long been used to study the wider economic implications of changes in crop yields. Yates and Strzepek (1998) show, for instance, that the impact of a reduced flow of the Nile on the economy of Egypt is much more severe without international trade than with, because trade would allow Egypt to focus on water-extensive production for export and import its food.

Older studies focused on the impact of climate change on patterns of specialization and trade, food prices, food security, and welfare (Kane et al., 1992; Reilly et al., 1994; Winters et al., 1998; Yates and Strzepek, 1998; Darwin and Kennedy, 2000; Darwin, 2004). This has been extended to land use (Lee, 2009; Ronneberger et al., 2009), water use (Kane et al., 1992; Calzadilla et al., 2011), and multiple stresses (Reilly et al., 2007). General equilibrium models have also been used to estimate the value of improved weather forecasts (Arndt and Bacou, 2000), a form of adaptation to climate change. Computable general equilibrium analysis has also been used to study selected impacts other than agriculture, notably SLR (Darwin and Tol, 2001; Bosello et al., 2007b), tourism (Berrittella et al., 2006; Bigano et al., 2008), human health (Bosello et al., 2006), and energy (see Section 10.2).

Bigano et al. (2008) study the joint, global impact on tourism and coasts in the 21st century, finding that changes in tourist demand dominate the welfare impacts of SLR. Kemfert (2002) and Eboli et al. (2010) estimate the joint, global effect on the world economy of a range of climate change impacts in the 21st century, but conflate general equilibrium and growth effects. Aaheim et al. (2010) analyze the economic effects of impacts of climate change on agriculture, forestry, fishery, energy demand, hydropower production, and tourism on the Iberian Peninsula. They find positive impacts on output in some sectors (agriculture,

electricity), negative impacts in other sectors (forestry, transport), and negligible ones in others (manufacturing, services). Ciscar et al. (2011) study the combined impact on agriculture, coasts, river floods, and tourism in the current European economy. They find an average welfare loss of 0.2 to 1.0% (depending on the SRES scenario) but there are large regional differences with losses in southern Europe and gains in northern Europe.

The following initial conclusions emerge. First, markets matter. Impacts are transmitted across locations—with local, regional, and global impacts—and across multiple sectors of the economy. For instance, landlocked countries are affected by SLR because their agricultural land increases in value as other countries face erosion and floods. Second, consumers and producers are often affected differently. The price increases induced by a reduction in production may leave producers better off while hurting consumers. Third, the distribution of the direct impacts can be very different than the distribution of the indirect effects. For instance, a loss of production may be advantageous to an individual company or country if the competition loses more. Fourth, a loss of productivity or productive assets in one sector leads to further losses in the rest of the economy. Fifth, markets offer options for adaptation, particularly possibilities for substitution. This changes the size, and sometimes the sign, of the impact estimate.

10.9.2. Aggregate Impacts

Since AR4, four new estimates of the global aggregate impact on human welfare of moderate climate change were published (Maddison and Rehdanz, 2011; Bosello et al., 2012; Roson and van der Mensbrugghe, 2012), including two estimates for warming greater than 3°C. Estimates agree on the size of the impact (small relative to economic growth), and 17 of the 20 impact estimates shown in Figure 10-1 are negative. Losses accelerate with greater warming, and estimates diverge. The new estimates have slightly widened the uncertainty about the economic impacts of climate.

Welfare impacts have been estimated with different methods, ranging from expert elicitation to econometric studies and simulation models. Different studies include different aspects of the impacts of climate change, but no estimate is complete; most experts speculate that excluded impacts are on balance negative. Estimates across the studies reflect different assumptions about inter-sectoral, inter-regional, and inter-temporal interactions, about adaptation, and about the monetary values of impacts. Aggregate estimates of costs mask significant differences in impacts across sectors, regions, countries, and populations. Relative to their income, economic impacts are higher for poorer people.

10.9.3. Social Cost of Carbon

The social cost of carbon (SCC) monetizes the expected welfare impacts of a marginal increase in carbon dioxide emissions in a given year (i.e., the welfare loss associated with an additional tonne of CO_2 emitted), aggregated across space, time, and probability (Tol, 2011). Figure 10-2 shows estimates published before AR4 and since, using the kernel density estimator by Tol (2013), extending the data with new estimates by Anthoff and Tol (2013b), Hope and Hope (2013), Hope (2013), and the Interagency Working Group on the Social Cost of Carbon (2013). Central estimates of the social cost of carbon have fallen slightly for all pure rates of time preference and the uncertainty has tightened, particularly for studies that use a pure rate of time preference of zero.

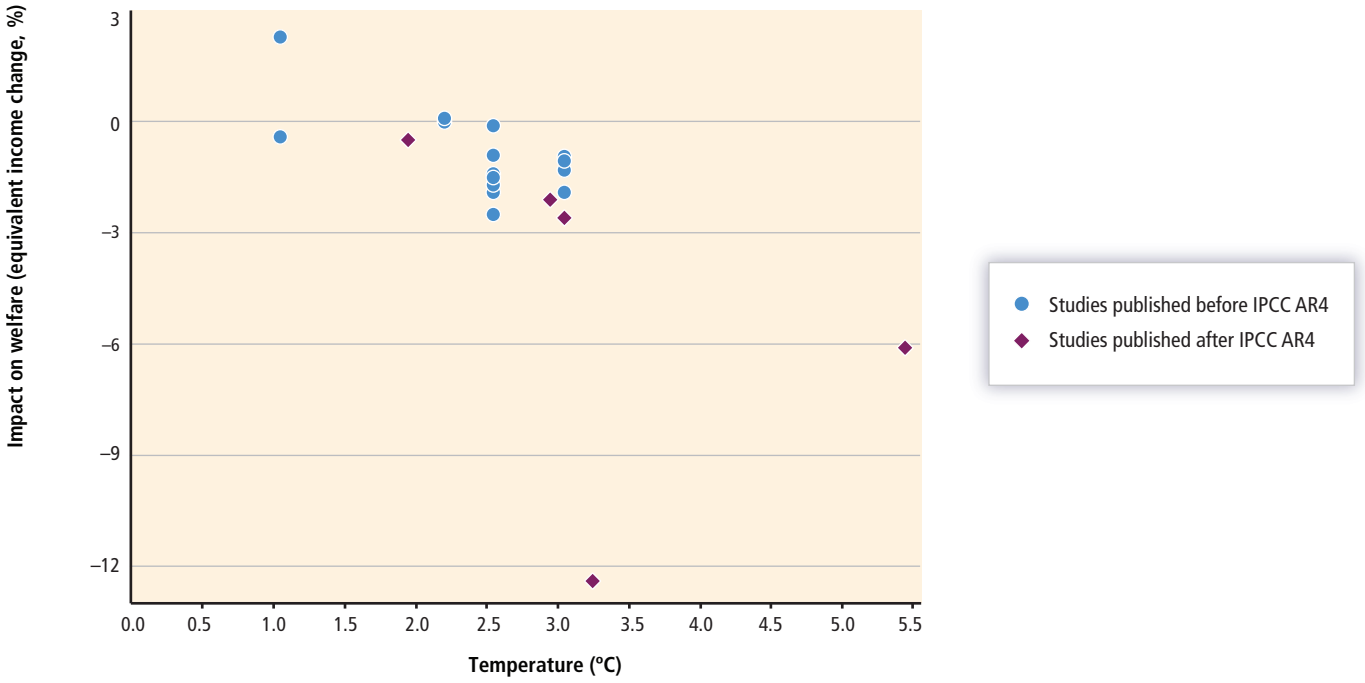


Figure 10-1 | Estimates of the total impact of climate change plotted against the assumed climate change (proxied by the increase in the global mean surface air temperature); studies published since IPCC AR4 are highlighted as diamonds; see Table SM10-1.

Table 10-9 | Selected statistical characteristics of the social cost of carbon: average (Avg) and standard deviation (SD), both in dollar per tonne of carbon, and number of estimates (*N*; number of studies in brackets).

PRTP	Post-AR4			Pre-AR4			All studies		
	Avg	SD	*N*	Avg	SD	*N*	Avg	SD	*N*
0%	270	233	97	745	774	89	585	655	142
1%	181	260	88	231	300	49	209	284	137
3%	33	29	35	45	39	42	40	36	186
All	241	233	462 (35)	565	822	323 (49)	428	665	785 (84)

Sources: See Section SM10.2 of the on-line supplementary material.

PRTP = pure rate of time preference.

See Table 10-9. For comparison, the EU ETS price in July 2013 was about US$21/tC.

Uncertainty in SCC estimates is high due to the uncertainty in underlying total damage estimates (see Section 10.9.2), uncertainty about future emissions, future climate change, future vulnerability and future valuation. The spread in estimates is also high due to disagreement regarding the appropriate framework for aggregating impacts over time (discounting), regions (equity weighing), and states of the world (risk aversion).

Quantitative analyses have shown that SCC estimates can vary by at least approximately two times depending on assumptions about future demographic conditions (Interagency Working Group on the Social Cost of Carbon, 2010), at least approximately three times owing to the incorporation of uncertainty (Kopp et al., 2012), and at least approximately four times owing to differences in discounting (Tol, 2011) or alternative damage functions (Ackerman and Stanton, 2012).

Concerns have been raised that the uncertainty about climate change is so large that the SCC would be unbounded (Weitzman, 2009), but this result is sensitive to assumptions about the utility function (Nordhaus, 2011; Buchholz and Schymura, 2012; Millner, 2013) and disappears when climate policy is formulated as balancing the risks of climate change against those of mitigation policy (Anthoff and Tol, 2013a; Hwang et al., 2013).

10.9.4. Effects on Growth

10.9.4.1. The Rate of Economic Growth

Climate change will also affect economic growth and development, but our understanding is limited. Fankhauser and Tol (2005) investigate four

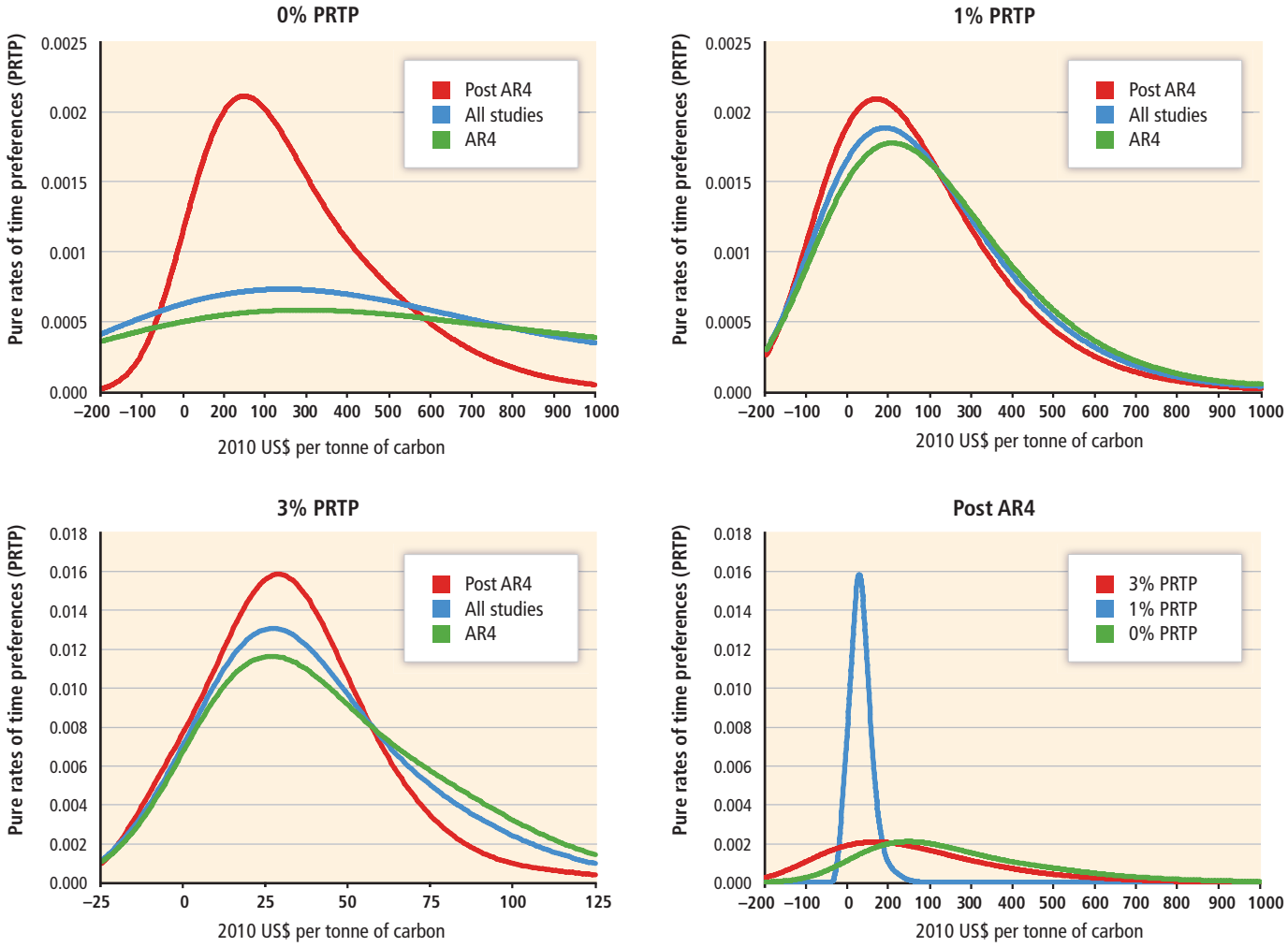


Figure 10-2 | Kernel densities of the social cost of carbon for all studies and studies before or after AR4 for three alternative pure rates of time preference (PRTP).

standard models of economic growth and three transmission mechanisms: economic production, capital depreciation, and the labor force. They find that, in three models, the fall in economic output is slightly larger than the direct impact on markets while in the fourth model (which emphasizes human capital accumulation) indirect impacts are 1.5 times as large. The difference can be understood as follows. In the three models, the impacts of climate change crowd out consumption and investment in physical capital, while in the fourth model investment in human capital is also crowded out; lower investment implies slower growth. Hallegatte (2005) reaches a similar conclusion. Hallegatte and Thery (2007), Hallegatte and Ghil (2008), and Hallegatte and Dumas (2009) highlight that the impact of climate change through natural hazards on economic growth can be amplified by market imperfections and the business cycle. In addition, Eboli et al. (2010) use a multi-sector, multi-region growth model, and find that the impact of climate change would lead to a 0.3% reduction of global GDP in 2050. Regional impacts are more pronounced, ranging from –1.0% in developing countries to +0.4% in Australia and Canada. In contrast, Garnaut (2008) finds –2.1% for Australia; the difference is due mainly to impacts on infrastructure (cf. Section 10.4). Sectoral results are varied too, with output changes ranging from +0.5% for power generation (to meet increased demand to air conditioning) to –0.7% for natural gas (as demand for space heating falls).

Using a biophysical model of the human body's ability to do work, Kjellstrom et al. (2009) find that by the end of the century climate change may reduce labor productivity by 11 to 27% in the humid (sub)tropics (depending on the SRES scenario; see Chapter 11 for further discussion). Assuming an output elasticity of labor of 0.8, this would reduce economic output in the affected sectors (involving heavy manual labor without air conditioning) by 8 to 22%. Although structural changes in the economy may well reduce the dependence on manual labor and air conditioning would be an effective adaptation, even the ameliorated impact would have a substantial, but as yet unquantified, impact on economic growth.

There are also statistical analyses of the relationship between climate and economic growth. Barrios et al. (2010) find that the decline in rainfall in the 20th century partly explains the economies of sub-Saharan Africa have grown more slowly than those of other developing regions. Brown et al. (2011) corroborate this. Dell et al. (2012) find that, in the second half of the 20th century, anomalously hot weather slowed down economic growth in poor countries, in both the agricultural and the industrial sectors. Dell et al. (2009) find that 1°C of warming would reduce income by 1.1% in the short run, and by 0.5% in the long run. The difference is due to adaptation. Horowitz (2009) finds a much larger effect: a 3.8% drop in income in the long run for one degree of warming. The impact of natural disasters on economic growth in the long-term is disputed, with studies reporting positive effects (Skidmore and Toya, 2002), negative effects (Raddatz, 2009), and no discernible effects (Cavallo et al., 2013).

10.9.4.2. Poverty Traps

Poverty is concentrated in the tropics and subtropics. This has led some analysts to the conclusion that a tropical climate is one in a complex of causes of poverty (which itself is a cause of poverty). We here focus on national economies, while Chapter 13 discusses groups of people in poverty. Gallup et al. (1999) emphasize the link between climate, disease, and poverty while Masters and McMillan (2001) focus on climate, agricultural pests, and poverty. Other studies (Acemoglu et al., 2001, 2002; Easterly and Levine, 2003) argue that climatic influence on development disappears if differences in human institutions (the rule of law, education, etc.) are accounted for. However, Van der Vliert (2008) demonstrates that climate affects human culture and thus institutions, but this has yet to be explored in the economic growth literature. Brown et al. (2011) find that weather affects economic growth in sub-Saharan Africa—particularly, drought decelerates growth. Jones and Olken (2010) find that exports from poor countries fall during hot years. Bloom et al. (2003) find limited support for an impact of climate (rather than weather) on past growth in a single-equilibrium model, but strong support in a multiple-equilibrium model: hot and wet conditions and large variability in rainfall reduce long-term growth in poor countries (but not in hot ones) and increase the probability of being poor.

Galor and Weil (1996) speculate about the existence of a climate-health-poverty trap. Strulik (2008), Bonds et al. (2010), Bretschger and Valente (2011), Gollin and Zimmermann (2012), and Ikefuji and Horii (2012) posit theoretical models and offer limited empirical support, while Tang et al. (2009) offers more rigorous empirical evidence. This is further supported by yet-to-be-published analyses (Gollin and Zimmermann, 2008; Ikefuji et al., 2010). Climate-related diseases such as malaria and diarrhea impair children's cognitive and physical development. This contributes to poverty in their later life so that there are limited means to protect their own children against these diseases. Furthermore, high infant mortality may induce parents to have many children so that the investment in education is spread thin. An increase in infant and child mortality and morbidity due to climate change could thus trap more people in poverty.

Zimmerman and Carter (2003) build a model in which the risk of natural disasters causes a poverty trap: at higher risk levels, households prefer assets with a safe but low return. Carter et al. (2007) find empirical support for this model at the household level, but van den Berg (2010) concludes the natural disaster itself has no discernible impact on investment choices. At the macroeconomic level, natural disasters disproportionally affect the growth rate of poor countries (Noy, 2009).

Devitt and Tol (2012) construct a model with a conflict-poverty trap, and show that climate change may exacerbate this. Bougheas et al. (1999, 2000) show that more expensive infrastructure, for example, because of frequent repairs after natural disasters, slows down economic growth and that there is a threshold infrastructure cost above which trade and specialization do not occur, suggesting another mechanism through which climate could cause a poverty trap. The implications of climate change have yet to be assessed.

10.9.5. Summary

In sum, estimates of the aggregate economic impact of climate change are relatively small but with a large downside risk. Estimates of the incremental damage per tonne of CO_2 emitted vary by two orders of

magnitude, with the assumed discount rate the main driver of the differences between estimates. The literature on the impact of climate and climate change on economic growth and development has yet to reach firm conclusions. There is agreement that climate change would slow economic growth, by a little according to some studies and by a lot according to other studies. Different economies will be affected differently. Some studies suggest that climate change may trap more people in poverty.

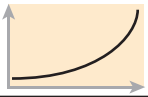
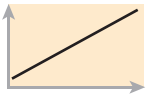
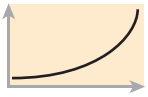
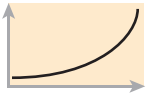
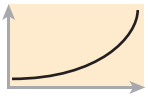
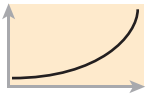
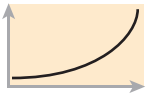
10.10. Summary; Research Needs and Priorities

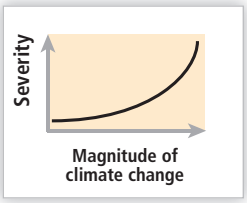
Table 10-10 summarizes the main findings. For each of the sectors discussed above, it gives the main climate drivers, the relationship between climate and impact (limited to less than linear, linear, and more than linear), the sign of the impacts (where needed split by economic actor), drivers other than climate change, and the relative importance of climate change.

Evaluating the economic aspects of the impacts has emerged as an active research area. Initial work has developed in a few key economic sectors and through economy-wide economic assessments. Data, tools, and methods continue to evolve to address additional sectors and more complex interactions among the sectors in the economic systems and a changing climate.

Based on a comprehensive assessment across economic sectors, few key sectors have been subject to detailed research. Multiple aspects of energy impacts have been assessed, but others remain to be evaluated, particularly economic impact assessments of adaptation both on existing and future infrastructure, but also the costs and benefits for future systems under differing climatic conditions. Studies focused on the impacts of

Table 10-10 | Summary of findings.

Sector	Climate change drivers	Sensitivity to climate change	Sign	Other drivers	Relative impact of climate change to other drivers
Winter tourism	• Temperature • Snow		Negative	• Population • Lifestyle • Income • Aging	Much less
Summer tourism	• Temperature • Rainfall • Cloudiness		Negative for suppliers in low altitudes and latitudes Positive for suppliers in high altitudes and latitudes Neutral for tourists	• Population • Income • Lifestyle • Aging	Much less
Cooling demand	• Temperature • Humidity • Hot spells		Positive for suppliers Negative for consumers	• Population • Income • Energy prices • Technology change	Less
Heating demand	• Temperature • Humidity • Cold spells		Negative for suppliers Positive for consumers	• Population • Income • Energy prices • Technology change	Less
Health services	• Temperature • Precipitation		Positive for suppliers Negative for consumers	• Aging • Income • Diet/lifestyle	Less
Water infrastructure and services	• Temperature • Precipitation • Storm Intensity • Seasonal Variability		Negative for water users Positive for suppliers Spatially heterogeneous	• Population • Income • Urbanization • Regulation	Less in developing countries Equal in developed countries
Transportation	• Temperature • Precipitation • Storm intensity • Seasonal variability • Freeze/thaw cycles		Negative for all users Positive for transport construction industry	• Population • Income • Urbanization • Regulation • Mode shifting • Consumer and commuter behavior	Much less in developing countries Less in developed countries
Insurance	• Temperature • Precipitation • Storm intensity • Seasonal variability • Freeze/thaw cycles		Negative for consumers Neutral for suppliers	• Population • Income • Regulation • Product innovation	Less or equal in developing countries Equal or more in developed countries



climate change on the energy sector indicate both potential benefits and detrimental impacts across developed and developing countries. In energy supply, the deployment of extraction, transport and processing infrastructure, power plants, and other installations are expected to proceed rapidly in developing countries in the coming decades to satisfy fast growing demand for energy. Designing newly deployed facilities with a view to projected changes in climate attributes and extreme weather patterns would require targeted inquiries into the impacts of climate change on the energy-related resource base, conversion, and transport technologies.

The economics of climate change impacts on transportation systems and their role in overall economic activity have yet to be well understood. For water related sectors, improved estimation of flood damages to economic sectors, research on economic impacts of ecosystems, rivers, lakes and wetlands, ecosystems service, and tourism and recreation are needed. Economic assessments of adaptation strategies such as water savings technologies, particularly for semiarid and arid developing countries, are also needed. Further, detailed studies are needed of the integrated impact of climate change on all water-dependent economic sectors, as existing studies do not examine competitiveness between water uses among sectors and economic productivity.

Although both tourism and recreation are sensitive to climate change, the literature on tourism is far more extensive. Current studies either have a rudimentary representation of the effect of weather and climate but a detailed representation of substitution between holiday destination and activities, or a detailed representation of the immediate impact of climate change but a rudimentary representation of alternatives to the affected destinations or activities.

Considerable research has been developed related to climate change impacts on insurance; however, only limited research is available on observed and projected changes in insured climate-related losses. To advance such research, climate science and risk research communities need to be better integrated. In addition, only few quantitative projection studies exist on regional markets including scenarios of changing hazard properties, exposure, vulnerability and adaption status, regulation, and availability of risk-based capital to indemnify disaster losses. Little research is available on the implications of climate change for banking/investment activities, in particular regarding the direct exposure of financial infrastructure. But also indirect effects through value losses in loan portfolios and assets as a result of physical damage and regulatory/reputational effects, together with liability and litigation risks, are under-investigated.

Little literature exists on potential climate impacts on other economic sectors, such as mining, manufacturing, and services (apart from health, insurance, and tourism), in particular assessments of whether these sectors are indeed sensitive to climate and climate change.

The spillover effects of the impacts of climate change in one sector on other markets are understood in principle, but the number of quantitative studies is too few to place much confidence in the numerical results. Similarly, the impact of climate and climate change on economic growth and development is not well understood, with some studies pointing to a small or negligible effect and other studies arguing for a large or dominant effect. A limited set of studies have evaluated the aggregate economic impact of climate change up to 3°C annual mean temperature rise, while only one study has evaluated larger temperature scenarios, suggesting considerable new analysis is warranted to improve confidence in the conclusions and investigation of a broader suite of Representative Concentration Pathways (RCPs).

References

Aaheim, A., H. Amundsen, T. Dokken, T. Ericson, and T. Wei, 2009: *A Macroeconomic Assessment of Impacts and Adaptation of Climate Change in Europe.* CICERO Report 2009:06, Center for International Climate and Environmental Research (CICERO), Oslo, Norway, 50 pp.

Aaheim, A., T. Dokken, S. Hochrainer, A. Hof, E. Jochem, R. Mechler, and D.P. van Vuuren, 2010: National responsibilities for adaptation strategies: lessons from four modelling framework. In: *Making Climate Change Work for Us: European Perspectives on Adaptation and Mitigation Strategies* [Hulme, M. and H. Neufeldt (eds.)]. Cambridge University Press, Cambridge, UK, pp. 87-112.

Aaheim, A., R.K. Chaturvedi, and A.D. Sagadevan, 2011a: Integrated modelling approaches to analysis of climate change impacts on forests and forest management. *Mitigation and Adaptation Strategies for Global Change*, **16(2)**, 247-266.

Aaheim, A., R. Gopalakrishnan, R.K. Chaturvedi, N.H. Ravindranath, A.D. Sagadevan, N. Sharma, and T. Wei, 2011b: A macroeconomic analysis of adaptation to climate change impacts on forests in India. *Mitigation and Adaptation Strategies for Global Change*, **16(2)**, 229-245.

Aakre, S., I. Banaszak, R. Mechler, D. Rübbelke, A. Wreford, and H. Kalirai, 2010: Financial adaptation to disaster risk in the European Union. *Mitigation and Adaptation Strategies for Global Change*, **15**, 721-736.

ABI, 2005: *Financial Risks of Climate Change*. Association of British Insurers (ABI) Report based on research by Climate Change Management in collaboration with Metroeconomica and in partnership with AIR Worldwide Corporation, ABI, London, UK, 39 pp.

Acemoglu, D., S. Johnson, and J.A. Robinson, 2001: The colonial origins of comparative development: an empirical investigation. *American Economic Review*, **91(4)**, 1369-1401.

Acemoglu, D., S. Johnson, and J.A. Robinson, 2002: Reversal of fortune: geography and institutions in the making of the modern world income distribution. *Quarterly Journal of Economics*, **117(4)**, 1231-1294.

Ackerman, F. and E.A. Stanton, 2012: Climate risks and climate prices: revisiting the social cost of carbon. *Economics: The Open-Access, Open-Assessment E-Journal*, **6(10)**, doi:10.5018/economics-ejournal.ja.2012-10.

Acosta-Moreno, R., J. Skea, A. Gacuhi, D.L. Greene, W. Moomaw, T. Okita, A. Riedacker, and T.V. Lien, 1995: Industry, energy, and transportation: impacts and adaptation. In: *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change* [Watson, R.T., M.C. Zinyowera, and R.H. Moss (eds.)]. Cambridge University Press, Cambridge, UK, New York, NY, USA, and Melbourne, Australia, pp. 365-398.

Adger, W.N., S. Agrawala, M.M.Q. Mirza, C. Conde, K. O'Brien, J. Pulhin, R. Pulwarty, B. Smit, and K. Takahashi, 2007: Assessment of adaptation practices, options, constraints and capacity. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 717-743.

Aerts, J.C.J.H. and W.J.W. Botzen, 2011: Climate change impacts on pricing long-term flood insurance: a comprehensive study for the Netherlands. *Global Environmental Change*, **21**, 1045-1060.

AgroClima, 2013: *AgroClima Informática Avanzada SA de CV*. AgroClima Informática Avanzada SA de CV (AgroClima), a ProAgro subsidiary specializing in climate information, Mexico, DF, Mexico, www.agroclima.com.mx/.

Allard, M., A. Fortier, D. Sarrazin, F. Calmels, D. Fortier, D. Chaumont, J.P. Savard, and Tarussov A., 2007: *L'Impact du Réchauffement Climatique sur les Aéroports du Nunavik: Caractéristiques du Pergélisol et Caractérisation des Processus de*

Dégradation des Pistes. Ressources naturelles Canada (Natural Resources Canada), Ottawa, ON, Canada, 184 pp.

Allison, E.H., A.L. Perry, M.-C. Badjeck, W.N. Adger, K. Brown, D. Conway, A.S. Halls, G.M. Pilling, J.D. Reynolds, N.L. Andrew, and N.K. Dulvy, 2009: Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries*, **10(2)**, 173-196.

Álvarez-Díaz, M. and J. Rosselló-Nadal, 2010: Forecasting British tourist arrivals in the Balearic Islands using meteorological variables. *Tourism Economics*, **16(1)**, 153-168.

Amelung, B. and A. Moreno, 2012: Costing the impact of climate change on tourism in Europe: results of the PESETA project. *Climatic Change*, **112(1)**, 83-100.

Amelung, B., S. Nicholls, and D. Viner, 2007: Implications of global climate change for tourism flows and seasonality. *Journal of Travel Research*, **45(3)**, 285-296.

Amengual, A., V. Homar, R. Romero, S. Alonso, and C. Ramis, 2012: Projections of the climate potential for tourism at local scales: application to Platja de Palma, Spain. *International Journal of Climatology*, **32(14)**, 2095-2107.

Anthoff, D. and R.S.J. Tol, 2013a: Climate policy under fat-tailed risk: an application of FUND. *Annals of Operations Research*, doi:10.1007/s10479-013-1343-2.

Anthoff, D. and R.S.J. Tol, 2013b: The uncertainty about the social cost of carbon: a decomposition analysis using FUND. *Climatic Change*, **117(3)**, 515-530.

Antonioni, G., S. Bonvicini, G. Spadoni, and V. Cozzani, 2009: Development of a framework for the risk assessment of Na-Tech accidental events. *Reliability Engineering and System Safety*, **94(9)**, 1442-1450.

Apipattanavis, S., K. Sabol, K.R. Molenaar, B. Rajagopalan, Y. Xi, B. Blackard, and S. Patil, 2010: Integrated framework for quantifying and predicting weather-related highway construction delays. *Journal of Construction Engineering and Management*, **136(11)**, 1160-1168.

Arkell, B.P. and G.J.C. Darch, 2006: Impact of climate change on London's transport network. *Municipal Engineer*, **159(ME4)**, 231-237.

Arndt, C. and M. Bacou, 2000: Economy-wide effects of climate variability and climate prediction in Mozambique. *American Journal of Agricultural Economics*, **82(3)**, 750-754.

Arndt, C., J. Thurlow, S. Kenneth, P. Chinowsky, A. Kuriakose, J. Neumann, and R. Nicholls, 2012: Impacts of climate change on development paths for Mozambique. *Review of International Economics*.

Arrow, K.J. and R.C. Lind, 1970: Uncertainty and the evaluation of public investment decisions. *The American Economic Review*, **60(3)**, 364-378.

Astrom, C., H. Orru, J. Rocklöv, G. Strandberg, K.L. Ebi, and B. Forsberg, 2013: Heat-related respiratory hospital admissions in Europe in a changing climate: a health impact assessment. *BMJ Open*, **3(1)**, e001842, doi:10.1136/bmjopen-2012-001842.

Banks, L.L., M.B. Shah, and M.E. Richards, 2007: Effective healthcare system response to consecutive Florida hurricanes. *American Journal of Disaster Medicine*, **2(6)**, 285-295.

Barlas, T.K. and G.A.M. Van Kuik, 2010: Review of state of the art in smart rotor control research for wind turbines. *Progress in Aerospace Sciences*, **46**, 1-27.

Barnett, B.J., C.B. Barrett, and J.R. Skees, 2008: Poverty traps and index-based risk transfer products. *World Development*, **36(10)**, 1766-1785.

Barredo, J.I., D. Sauri, and M.C. Llasat, 2012: Assessing trends in insured losses from floods in Spain 1971-2008. *Natural Hazards and Earth System Sciences*, **12(5)**, 1723-1729, doi:10.5194/nhess-12-1723-2012.

Barrieu, P. and H. Loubergé, 2009: Hybrid cat bonds. *The Journal of Risk and Insurance*, **76(3)**, 547-578.

Barrios, S., L. Bertinelli, and E. Strobl, 2010: Trends in rainfall and economic growth in Africa: a neglected cause of the African growth tragedy. *Review of Economics and Statistics*, **92(2)**, 350-366.

Barthel, F. and E. Neumayer, 2012: A trend analysis of normalized insured damage from natural disasters. *Climatic Change*, **113**, 215-237, doi:10.1007/s10584-011-0331-2.

Barthelmie, R.J., F. Murray, and S.C. and Pryor, 2008: The economic benefit of short-term forecasting for wind energy in the UK electricity market. *Energy Policy*, **36**, 1687-1696.

Becken, S., 2005: Harmonising climate change adaptation and mitigation: the case of tourist resorts in Fiji. *Global Environmental Change*, **15(4)**, 381-393.

Becken, S. and J. Hay, 2007: *Tourism and Climate Change: Risks and Opportunities.* Channel View Publications, Bristol, UK, 352 pp.

Becker, A., S. Inoue, M. Fischer, and B. Schwegler, 2011: Climate change impacts on international seaports: knowledge, perceptions, and planning efforts among port adminstrators. *Climatic Change*, **10(1-2)**, 5-29.

Belle, N. and B. Bramwell, 2005: Climate change and small island tourism: policy maker and industry perspectives in Barbados. *Journal of Travel Research*, **44(1)**, 32-41.

Bengtsson, L., K. Hodges, and E. Roeckner, 2006: Storm tracks and climate change. *Journal of Climate*, **19**, 3518-3543.

Berrittella, M., A. Bigano, R. Roson, and R.S.J. Tol, 2006: A general equilibrium analysis of climate change impacts on tourism. *Tourism Management*, **27(5)**, 913-924.

Bicknell, S. and P. McManus, 2006: The canary in the coalmine: Australian ski resorts and their response to climate change. *Geographical Research*, **44(4)**, 386-400.

Biener, C. and M. Eling, 2012: Insurability in microinsurance markets: an analysis of problems and potential solutions. *The Geneva Papers*, **37(1)**, 77-107, doi:10.1057/gpp.2011.29.

Bigano, A., J.M. Hamilton, and R.S.J. Tol, 2006: The impact of climate on holiday destination choice. *Climatic Change*, **76(3-4)**, 389-406.

Bigano, A., J.M. Hamilton, and R.S.J. Tol, 2007: The impact of climate change on domestic and international tourism: a simulation study. *Integrated Assessment*, **7(1)**, 25-49.

Bigano, A., F. Bosello, R. Roson, and R.S.J. Tol, 2008: Economy-wide impacts of climate change: a joint analysis for sea level rise and tourism. *Mitigation and Adaptation Strategies for Global Change*, **13(8)**, 765-791.

Block, P. and K.M. Strzepek, 2012: Power ahead: meeting Ethiopia's energy needs under a changing climate. *Review of International Economics*, **6(3)**, 476-488.

Bloom, A., V. Kotroni, and K. Lagouvardos, 2008: Climate change impact of wind energy availability in the Eastern Mediterranean using the regional climate model PRECIS. *Natural Hazards and Earth System Sciences*, **8**, 1249-1257.

Bloom, D.E., D. Canning, and J. Sevilla, 2003: Geography and poverty traps. *Journal of Economic Growth*, **8(4)**, 355-378.

Bonds, M.H., D.C. Keenan, P. Rohani, and J.D. Sachs, 2010: Poverty trap formed by the ecology of infectious diseases. *Proceedings of the Royal Society B*, **277(1685)**, 1185-1192.

Borch, K., 1962: Equilibrium in a reinsurance market. *Econometrica*, **30(3)**, 424-444.

Bosello, F., R. Roson, and R.S.J. Tol, 2006: Economy-wide estimates of the implications of climate change: human health. *Ecological Economics*, **58(3)**, 579-591.

Bosello, F., E. De Cian, and R. Roson, 2007a: *Climate Change, Energy Demand and Market Power in a General Equilibrium Model of the World Economy*. CMCC Research Paper No. 10, Centro Euro-Mediterraneo per i Cambiamenti Climatici, Climate Impacts and Policy Division (CMCC), Lecce, Italy,16 pp.

Bosello, F., R. Roson, and R.S.J. Tol, 2007b: Economy-wide estimates of the implications of climate change: sea level rise. *Environmental and Resource Economics*, **37(3)**, 549-571.

Bosello, F., C. Carraro, and E. De Cian, 2009: *An Analysis of Adaptation as a Response to Climate Change*. Working Paper No. 26 Department of Economics, Ca' Foscari University of Venice, Venice, Italy, 60 pp.

Bosello, F., F. Eboli, and R. Pierfederici, 2012: Assessing the economic impacts of climate change. *Review of Energy Environment and Economics*, **Re3**, doi:10.7711/feemre3.2012.02.002.

Botzen, W.J.W. and J.C.J.M. van den Bergh, 2008: Insurance against climate change and flooding in the Netherlands: present, future, and comparison with other countries. *Risk Analysis*, **28(2)**, 413-426.

Botzen, W.J.W. and J.C.J.M. van den Bergh, 2009: Bounded rationality, climate risks, and insurance: is there a market for natural disasters? *Land Economics*, **85(2)**, 265-278.

Botzen, W.J.W. and J.C.J.M. van den Bergh, 2012: Monetary valuation of insurance against flood risk under climate change. *International Economic Review*, **53(3)**, 1005-1025.

Botzen, W.J.W., J.C.J.H. Aerts, and J.C.J.M. van den Bergh, 2009: Willingness of homeowners to mitigate climate risk through insurance. *Ecological Economics*, **68**, 2265-2277.

Botzen, W.J.W., J.C.J.M. van den Bergh, and L.M. Bouwer, 2010a: Climate change and increased risk for the insurance sector: a global perspective and an assessment for the Netherlands. *Natural Hazards*, **52**, 577-598.

Botzen, W.J.W., L.M. Bouwer, and J.C.J.M. van den Bergh, 2010b: Climate change and hailstorm damage: empirical evidence and implications for agriculture and insurance. *Resource and Energy Economics*, **32**, 341-362.

Bougheas, S., P.O. Demetriades, and E.L.W. Morgenroth, 1999: Infrastructure, transport costs and trade. *Journal of International Economics*, **47(1)**, 169-189.

Bougheas, S., P.O. Demetriades, and T.P. Mamuneas, 2000: Infrastructure, specialization, and economic growth. *Canadian Journal of Economics*, **33(2)**, 506-522.

Bourdeau, P., 2009: From après-ski to après-tourism: the Alps in transition? Reflections based on the French situation. *Revue de Geographie Alpine*, **97(3)**, rga.revues.org/1049.

Bouwer, L.M., 2011: Have disaster losses increased due to anthropogenic climate change? *Bulletin of the American Meteorological Society*, **92**, 39-46.

Bouwer, L.M., R.P. Crompton, E. Faust, P. Höppe, and R.A. Pielke Jr., 2007: Confronting disaster losses. *Science*, **318(5851)**, 753.

Boyd, R. and M.E. Ibarraran, 2009: Extreme climate events and adaptation: an exploratory analysis of drought in Mexico. *Environment and Development Economics*, **14**, 371-395.

Brander, L.M., K. Rehdanz, R.S.J. Tol, and P.H.J. van Beukering, 2012: The economic impact of ocean acidification on coral reefs. *Climate Change Economics*, **3(1)**, 1-29.

Breisinger, C., T. Zhu, P. Al Riffai, G. Nelson, R. Robertson, J. Funes, and D. Verner, 2013: Global and local economic impacts of climate change in Syria and options for adaptation. *Climate Change Economics*, **4(1)**, doi:10.1142/S2010007813500024.

Bretschger, L. and S. Valente, 2011: Climate change and uneven development. *Scandinavian Journal of Economics*, **113(4)**, 825-845.

Brimble, M. and J. Stewart, 2009: The financial sector and climate change risks, opportunities and overall preparedness. In: *APABIS 2009: Proceedings of the Asia Pacific Academy of Business in Society Conference: Finding Solutions to Global Problems through Stakeholder Engagement, New Social Partnerships and Strategic Alliances for a Sustainable Enterprise Economy, 5 – 6 November 2009, Brisbane, Australia*. Asia Pacific Academy of Business in Society (APABIS), Hamilton, New Zealand, doi:10.2139/ssrn.1460676.

Brown, C., R. Meeks, K. Hunu, and W. Yu, 2011: Hydroclimate risk to economic growth in sub-Saharan Africa. *Climatic Change*, **106(4)**, 621-647.

Bruggeman, V., M.G. Faure, and K. Fiore, 2010: The government as reinsurer of catastrophe risks. *The Geneva Papers*, **35**, 369-390.

Buchholz, W. and M. Schymura, 2012: Expected utility theory and the tyranny of catastrophic risks. *Ecological Economics*, **77**, 234-239.

Buckley, L.B. and M.S. Foushee, 2012: Footprints of climate change in US national park visitation. *International Journal of Biometeorology*, **56(6)**, 1173-1177.

Bujosa, A. and J. Rosselló, 2012: Climate change and summer mass tourism: the case of Spanish domestic tourism. *Climatic Change*, **117(1-2)**, 363-375.

Burby, J.R., 2006: Hurricane Katrina and the paradoxes of government disaster policy: bringing about wise governmental decisions for hazardous areas. *The ANNALS of the American Academy of Political and Social Science*, **604**, 171-191.

Buzinde, C.N., D. Manuel-Navarrete, D. Kerstetter, and M. Redclift, 2010a: Representations and adaptation to climate change. *Annals of Tourism Research*, **37(3)**, 581-603.

Buzinde, C.N., D. Manuel-Navarrete, E.E. Yoo, and D. Morais, 2010b: Tourists' perceptions in a climate of change: eroding destinations. *Annals of Tourism Research*, **37(2)**, 333-354.

Byass, P., d.C. Maximilian, J.G. Wendy, L. Lucie, M. Affette, A.S. Osman, M.T. Stephen, and Z. Basia, 2013: Reflections on the global burden of disease 2010 estimates. *PLoS Med*, **10(7)**, e1001477, doi:10.1371/journal.pmed.1001477.

Bye, T., A. Bruvoll, and F.R. Aune, 2008: Inflow shortages in deregulated power markets – reasons for concern? *Energy Economics*, **30(4)**, 1693-1711.

Callaway, J.M., D.B. Louw, and M. Hellmuth, 2012: Benefits and costs of measures for coping with water and climate change: Berg River Basin, South Africa. In: *Climate Change Adaptation in the Water Sector* [Ludwig, F., P. Kabat, H. van Schaik, and M. van der Valk (eds.)]. Earthscan, London, UK and Sterling, VA, USA, pp. 205-226.

Calzadilla, A., K. Rehdanz, and R.S.J. Tol, 2011: Trade liberalization and climate change: a computable general equilibrium analysis of the impacts on global agriculture. *Water*, **3(2)**, 526-550.

Candel, F.M., 2007: Climate change and the global insurance industry: impacts and problems in Latin America. *The Geneva Papers*, **32**, 29-34.

Carter, M.R., P.D. Little, T. Mogues, and W. Negatu, 2007: Poverty traps and natural disasters in Ethiopia and Honduras. *World Development*, **35(5)**, 835-856.

Carthey, J., V. Chandra, and M. Loosemore, 2009: Adapting Australian health facilities to cope with climate-related extreme weather events. *Journal of Facilities Management*, **7**, 36-51.

Cavallo, E., E. Galiani, I. Noy, and J. Pantano, 2013: Catastrophic natural disasters and economic growth. *Review of Economics and Statistics*, **95(5)**, 1549-1561.

Cavan, G., J.F. Handley, J. Aylen, K. Albertson, J. McMorrow, S. Lindley, and D. McEvoy, 2006: Climate change and the visitor economy in the uplands. *International Journal of Biodiversity Science and Management*, **2(3)**, 170-173.

CCSP, 2007: *Effects of Climate Change on Energy Production and Use in the United States* [Wilbanks, T.J. (coordinating author), V. Bhatt, D.E. Bilello, S.R. Bull, J. Ekmann, W.C. Horak, Y.J. Huang, M.D. Levine, M.J. Sale, D.K. Schmalzer, and M.J. Scott (authors)]. U.S. Climate Change Science Program Synthesis and Assessment Product 4.5, Report by the U.S. Climate Change Science Program (CCSP) and the Subcommittee on Global Change Research, U.S. Department of Energy, Office of Biological & Environmental Research, Washington, DC, USA, 144 pp.

CCSP, 2008: *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I* [Potter, J., V. Burkett, M. Savonis, and D. Dokken (eds.)]. U.S. Climate Change Science Program Synthesis and Assessment Product 4.7, Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, U.S. Department of Transportation, Washington, DC, USA, 445 pp.

City of Chicago, 2008: *Chicago Climate Action Plan: Our City, Our Future.* City of Chicago, Chicago Climate Task Force (CCTF), Chicago, IL, USA, 56 pp.

Ceron, J.-P. and G. Dubois, 2005: The potential impacts of climate change on French tourism. *Current Issues in Tourism*, **8(2-3)**, 125-139.

Changnon, S.A., 2005: Economic impacts of climate conditions in the United States: past, present, and future – an editorial essay. *Climatic Change*, **68(1-2)**, 1-9.

Changnon, S.A., 2007: Catastrophic winter storms: an escalating problem. *Climatic Change*, **84**, 131-139.

Changnon, S.A., 2008: Assessment of flood losses in the United States. *Journal of Contemporary Water Research & Education*, **138**, 38-44.

Changnon, S.A., 2009a: Characteristics of severe Atlantic hurricanes in the United States: 1949-2006. *Natural Hazards*, **48**, 329-337.

Changnon, S.A., 2009b: Increasing major hail losses in the U.S. *Climatic Change*, **96(1-2)**, 161-166.

Channing, A., P Chinowsky, S Robinson, K. Strzepek, F. Tarp, and J. Thurlow, 2012: Economic development under climate change. *Review of International Economics*, **16(3)**, 369-377, DOI: 10.1111/j.1467-9361.2012.00668.x

Chantarat, S., A.G. Mude, C.B. Barrett, and M.R. Carter, 2013: Designing index-based livestock insurance for managing asset risk in northern Kenya. *The Journal of Risk and Insurance*, **80(1)**, 205-237.

Chapman, L., 2007: Transport and climate change: a review. *Journal of Transport Geography*, **15**, 354-367.

Charpentier, A., 2008: Insurability of climate risks. *The Geneva Papers*, **33**, 91-109.

Chen, C.-C., D. Gillig, and B.A. McCarl, 2001: Effects of climatic change on a water dependent regional economy: a study of the Texas Edwards Aquifer. *Climatic Change*, **49(4)**, 397-409.

Cheng, C.S., Q. Li, G. Li, and H. Auld, 2012: Climate change and heavy rainfall-related water damage insurance claims and losses in Ontario, Canada. *Journal of Water Resource and Protection*, **4(2)**, 49-62, doi:10.4236/jwarp.2012.42007.

Chinowsky, P. and C. Arndt, 2012: Climate change and roads: a dynamic stressor–response model. *Review of Development Economics*, **16(3)**, 448-462.

Chinowsky, P., K.M. Strzepek, P. Larsen, and A. Opdahl, 2010: Adaptive climate response cost models for infrastructure. *ASCE Journal of Infrastructure Systems*, **16**, 173-181.

Chinowsky, P., C. Hayles, A. Schwwikert, N. Strzepek, K.M. Strzepek, and C.A. Schlosser, 2011: Climate change: comparative impact on developing and developed countries. *The Engineering Project Organization Journal*, **1(1)**, 67-80.

Chinowsky, P.S., A.E. Schweikert, N.L. Strzepek, and K.M. Strzepek, 2013: *Infrastructure and Climate Change: Impacts and Adaptations for the Zambezi River Valley.* UNU-WIDER Working Paper, WP/2013/041, United Nations University-World Institute for Development Economics Research (UNU-WIDER), Helsinki, Finland, 14 pp.

Choi, O. and A. Fisher, 2003: The impacts of socioeconomic development and climate change on severe weather catastrophe losses: Mid-Atlantic Region (MAR) and the U.S. *Climatic Change*, **58(1-2)**, 149-170.

Ciscar, J.-C., A. Iglesias, L. Feyen, L. Szabó, D. Van Regemorter, B. Amelung, R. Nicholls, P. Watkiss, O.B. Christensen, R. Dankers, L. Garrote, C.M. Goodess, A. Hunt, A. Moreno, J. Richards, and A. Soria, 2011: Physical and economic consequences of climate change in Europe. *Proceedings of the National Academy of Sciences of the United States of America*, **108(7)**, 2678-2683.

Clarke, D.J. and D. Grenham, 2012: Microinsurance and natural disasters: challenges and options. *Environmental Science & Policy*, **27(Suppl. 1)**, S89-S98.

Cogan, D.G., M. Good and E. McAteer, 2008: *Corporate Governance and Climate Change: The Banking Sector.* Ceres Report produced by the RiskMetrics Group, Ceres, Boston, MA, USA, 55 pp.

Collier, B., J. Skees, and B. Barnett, 2009: Weather index insurance and climate change: opportunities and challenges in lower income countries. *The Geneva Papers*, **34**, 401-424.

Cooley, S.R. and S.C. Doney, 2009: Anticipating ocean acidification's economic consequences for commercial fisheries. *Environmental Research Letters*, **4(2)**, doi:10.1088/1748-9326/4/2/024007.

Coombes, E.G., A.P. Jones, and W.J. Sutherland, 2009: The implications of climate change on coastal visitor numbers: a regional analysis. *Journal of Coastal Research*, **25(4)**, 981-990.

Corti, T., V. Muccione, P. Köllner-Heck, D. Bresch, and S.I. Seneviratne, 2009: Simulating past droughts and associated building damages in France. *Hydrology and Earth System Sciences*, **13**, 1739-1747.

Courbage, C., M. Orie, and W.R. Stahel, 2012: 2011 Thai floods and insurance. In: *The Geneva Reports – Risk and Insurance Research No. 5. Extreme Events and Insurance: 2011 annus horribilis* [Courbage, C. and W.R. Stahel (eds.)]. The Geneva Association, The International Association for the Study of Insurance Economics, Geneva, Switzerland, pp. 121-132.

Crompton, R.P. and K.J. McAneney, 2008: Normalised Australian insured losses from meteorological hazards: 1967-2006. *Environmental Science & Policy*, **11**, 371-378.

Crompton, R.P., R.A.J. Pielke, and K.J. McAneney, 2011: Emergence timescales for detection of anthropogenic climate change in US tropical cyclone loss data. *Environmental Research Letters*, **6(1)**, 014003, doi:10.1088/1748-9326/6/1/014003.

Cruz, A.M. and E. Krausmann, 2013: Vulnerability of the oil and gas sector to climate change and extreme weather events. *Climatic Change*, **121(1)**, 41-53.

Cummins, J.D., 2012: CAT bonds and other risk-linked securities: product design and evolution of the market. In: *The Geneva Reports – Risk and Insurance Research No. 5. Extreme Events and Insurance: 2011 annus horribilis* [Courbage, C. and W.R. Stahel (eds.)]. The Geneva Association, The International Association for the Study of Insurance Economics, Geneva, Switzerland, pp. 39-61.

Cummins, J.D. and O. Mahul, 2009: *Catastrophe Risk Financing in Developing Countries: Principles for Public Intervention.* The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 268 pp.

Cummins, J.D. and M.A. Weiss, 2009: Convergence of insurance and financial markets: hybrid and securitized risk-transfer solutions. *The Journal of Risk and Insurance*, **76(3)**, 493-545.

Dailey, P., M. Huddleston, S. Brown, and D. Fasking, 2009: *The Financial Risks of Climate Change: Examining the Financial Implications of Climate Change using Climate Models and Insurance Catastrophe Risk Models.* ABI Research Paper No. 19, Report by AIR Worldwide Corporation and the Met Office, The Association of British Insurers, London, UK, 107 pp.

Damigos, D., 2012: Monetizing the impacts of climate change on the Greek mining sector. *Mitigation and Adaptation Strategies for Global Change*, **17(8)**, 865-878.

Darwin, R.F., 2004: Effects of greenhouse gas emissions on world agriculture, food consumption, and economic welfare. *Climatic Change*, **66(1-2)**, 191-238.

Darwin, R.F. and D. Kennedy, 2000: Economic effects of CO_2 fertilization of crops: transforming changes in yield into changes in supply. *Environmental Modeling and Assessment*, **5**, 157-168.

Darwin, R.F. and R.S.J. Tol, 2001: Estimates of the economic effects of sea level rise. *Environmental and Resource Economics*, **19(2)**, 113-129.

Dasgupta, S., M. Huq, H. Khan, Z. Ahmed, N. Mukherjee, M. Khan, and K. Pandey, 2010: *Vulnerability of Bangladesh to Cyclones in a Changing Climate: Potential Damages and Adaptation Cost.* Policy Research Working Paper No. 5280, The World Bank, Development Research Group, Environment and Energy Team, Washington, DC, USA, 54 pp.

Daugherty, D.J., D.L. Buckmeier, and P.K. Kokkanti, 2011: Sensitivity of recreational access to reservoir water level variation: an approach to identify future access needs in reservoirs. *North American Journal of Fisheries Management*, **31(1)**, 63-69.

Dawson, J. and D. Scott, 2010: Climate change and tourism in the great lakes region: a summary of risks and opportunities. *Tourism in Marine Environments*, **6(2-3)**, 119-132.

Dawson, J. and D. Scott, 2013: Managing for climate change in the alpine ski sector. *Tourism Management*, **35**, 244-254.

Dawson, J., D. Scott, and G. McBoyle, 2009: Climate change analogue analysis of ski tourism in the northeastern USA. *Climate Research*, **39(1)**, 1-9, doi:10.3354/cr00793.

Day, J., N. Chin, S. Sydnor, and K. Cherkauer, 2013: Weather, climate, and tourism performance: a quantitative analysis. *Tourism Management Perspectives*, **5**, 51-56.

De Bruin, K., R.B. Dellink, A. Ruijs, L. Bolwidt, A. Van Buuren, J. Graveland, R.S. De Groot, P.J. Kuikman, S. Reinhard, and R.P. Roetter, 2009: Adapting to climate change in The Netherlands: an inventory of climate adaptation options and ranking of alternatives. *Climatic Change*, **95(1-2)**, 23-45.

de Cian, E., E. Lanzi, and R. Roson, 2013: Seasonal temperature variations and energy demand: a panel cointegration analysis for climate change impact assessment. *Climatic Change*, **116(3-4)**, 805-825.

De Freitas, C.R., D. Scott, and G. McBoyle, 2008: A second generation climate index for tourism (CIT): specification and verification. *International Journal of Biometeorology*, **52(5)**, 399-407.

de Lucena, A.F.P., R. Schaeffer, and A.S. Szklo, 2010: Least-cost adaptation options for global climate change impacts on the Brazilian electric power system. *Global Environmental Change*, **20(2)**, 342-350.

de Nooij, M., R. Lieshout, and C. Koopmans, 2009: Optimal blackouts: empirical results on reducing the social cost of electricity outages through efficient regional rationing. *Energy Economics*, **31(3)**, 342-347.

Dell, J.J. and P. Pasteris, 2010: Adaptation in the oil and gas industry to projected impacts of climate change. In: *SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production, 2010, 12-14 April, Rio de Janeiro, Brazil*. Vol. 1, Society of Petroleum Engineers (SPE), Richardson, TX, USA, pp. 333-348.

Dell, M., B.F. Jones, and B.A. Olken, 2009: Temperature and income: reconciling new cross-sectional and panel estimates. *American Economic Review*, **99(2)**, 198-204.

Dell, M., B.F. Jones, and B.A. Olken, 2012: Temperature shocks and economic growth: evidence from the last half century. *American Economic Journal: Macroeconomics*, **4(3)**, 66-95.

Denstadli, J.M., J.K.S. Jacobsen, and M. Lohmann, 2011: Tourist perceptions of summer weather in Scandinavia. *Annals of Tourism Research*, **38(3)**, 920-940.

Devitt, C. and R.S.J. Tol, 2012: Civil war, climate change, and development: a scenario study for sub-Saharan Africa. *Journal of Peace Research*, **49(1)**, 129-145.

DOE, 2007: *Concentrating Solar Power Commercial Application Study: Reducing Water Consumption of Concentrating Solar Power Electricity Generation.* U.S. Department of Energy (DOE) Report to Congress, DOE, Washington, DC, USA, 24 pp.

DOE, 2009: *An Analysis of the Effects of Drought Conditions on Electric Power Generation in the United States.* DOE/NETL-2009/1365, U.S. Department of Energy (DOE) and National Energy Technology Laboratory (NREL), DOE, Washington, DC, USA, 32 pp.

DOE, 2013: *U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather.* DOE/PI-0013, U.S. Department of Energy, Office of Policy and International Affairs (DOE-PI) and the National Energy Technology Laboratory (NREL), DOE, Washington, DC, USA, 81 pp.

Donat, M.G., G.C. Leckebusch, S. Wild, and U. Ulbrich, 2011: Future changes in European winter storm losses and extreme wind speeds detected from GCM and RCM multi-model simulations. *Natural Hazards and Earth System Sciences*, **11**, 1351-1370.

Doney, S.C., V.J. Fabry, R.A. Feely, and J.A. Kleypas, 2009: Ocean acidification: the other CO_2 problem. *Annual Review of Marine Science*, **1**, 169-192.

Dore, M. and I. Burton, 2001: *The Costs of Adaptation to Climate Change in Canada: A Stratified Estimate by Sectors and Regions – Social Infrastructure.* Climate Change Laboratory, Brock University, St Catharines, ON, Canada, 338 pp.

DOT, 2002: *The Potential Impacts of Climate Change on Transportation*. Federal Research Partnership Workshop October 1-2, 2002 held at the Brookings Institution, Washington, DC, USA, Summary and Discussion Papers, U.S. Department of Transportation Center for Climate Change and Environmental Forecasting (DOT), Washington, DC, USA, 263 pp.

Droogers, P., 2009: *Climate Change and Hydropower, Impact and Adaptation Costs: Case Study Kenya.* FutureWater Report 85, FutureWater, Wageningen, Netherlands, 27 pp.

Dunne, J., S. R., and J. J., 2013: Reductions in labour capacity from heat stress under climate warming. *Nature Climate Change*, **3(3)**, 1-4.

Duus-Otterström, G. and S.C. Jagers, 2011: Why (most) climate insurance schemes are a bad idea. *Environmental Politics*, **20(3)**, 322-339, doi:10.1080/09644016.2011.573354.

Easterly, W. and R. Levine, 2003: Tropics, germs, and crops: how endowments influence economic development. *Journal of Monetary Economics*, **50(1)**, 3-39.

Ebert, I., 2010: Legal aspects of U.S. claims based on greenhouse gas emissions. In: *Liability for Climate Change? Experts' Views on a Potential Emerging Risk*. Munich Re, Munich, Germany, pp. 14-15.

Ebi, K.L., 2008: Adaptation costs for climate change-related cases of diarrhoeal disease, malnutrition, and malaria in 2030. *Globalization and Health*, **4(9)**, doi:10.1186/1744-8603-4-9.

Ebinger, J. and W. Vergara, 2011: *Climate Impacts on Energy Systems: Key Issues for Energy Sector Adaptation.* The International Bank for Reconstruction and Development / The World Bank and Energy Sector Management Assistance Program (ESMAP), The World Bank, Washington, DC, USA, 178 pp.

Eboli, F., R. Parrado, and R. Roson, 2010: Climate-change feedback on economic growth: explorations with a dynamic general equilibrium model. *Environment and Development Economics*, **15(5)**, 515-533.

Eide, A., 2008: An integrated study of economic effects of and vulnerabilities to global warming on the Barents Sea cod fisheries. *Climatic Change*, **87(1-2)**, 251-262.

Eide, A. and K. Heen, 2002: Economic impacts of global warming. A study of the fishing industry in North Norway. *Fisheries Research*, **56(3)**, 261-274.

Eijgelaar, E., C. Thaper, and P. Peeters, 2010: Antarctic cruise tourism: the paradoxes of ambassadorship, "last chance tourism" and greenhouse gas emissions. *Journal of Sustainable Tourism*, **18(3)**, 337-354.

Eisenack, K. and R. Stecker, 2012: A framework for analyzing climate change adaptations as actions. *Mitigation and Adaptation Strategies for Global Change*, **17(3)**, 243-260.

Eisenack, K., R. Stecker, D. Reckien, and E. Hoffmann, 2012: Adaptation to climate change in the transport sector: a review of actions and actors. *Mitigation and Adaptation Strategies for Global Change*, **17**, 451-469.

Ekman, J., 2013: Climate change impacts on coal from resource assessment through to environmental remediation. *Climatic Change*, **21(1)**, 27-39.

Elsasser, H. and R. Bürki, 2002: Climate change as a threat to tourism in the Alps. *Climate Research*, **20(3)**, 253-257.

Emanuel, K., 2011: Global warming effects on U.S. hurricane damage. *Weather, Climate and Society*, **3(4)**, 261-268.

Endler, C. and A. Matzarakis, 2010a: Climatic potential for tourism in the Black Forest, Germany – winter season. *International Journal of Biometeorology*, **55(3)**, 339-351.

Endler, C. and A. Matzarakis, 2010b: Analysis of high-resolution simulations for the Black Forest region from a point of view of tourism climatology – a comparison between two regional climate models (REMO and CLM). *Theoretical and Applied Climatology*, **103(3-4)**, 427-440.

Endler, C. and A. Matzarakis, 2011: Climate and tourism in the Black Forest during the warm season. *International Journal of Biometeorology*, **55(2)**, 173-186.

Endler, C., K. Oehler, and A. Matzarakis, 2010: Vertical gradient of climate change and climate tourism conditions in the Black Forest. *International Journal of Biometeorology*, **54(1)**, 45-61.

EPA, 2001: *Technical Development Document for the Final Regulations Addressing Cooling Water Intake Structures for the New Facilities.*, EPA-821-R-01-036, Office of Water, U.S. Environmental Protection Agency (EPA), Washington, DC, USA, 269 pp.

Eskeland, G.S. and T.K. Mideksa, 2010: Electricity demand in a changing climate. *Mitigation and Adaptation Strategies for Global Change*, **15(8)**, 877-897.

Falk, M., 2013: Impact of long-term weather on domestic and foreign winter tourism demand. *International Journal of Tourism Research*, **15(1)**, 1-17, doi:10.1002/jtr.865.

Fankhauser, S. and R.S.J. Tol, 2005: On climate change and economic growth. *Resource and Energy Economics*, **27(1)**, 1-17.

Fant, C., Y. Gebretsadik, and K.M. Strzepek, 2013: Impact of climate change on crops, irrigation, and hydropower in the Zambezi River Basin. UNU-WIDER Working Paper No. 2013/039, Helsinki, Finland, 26 pp. ISBN 978-92-9230-61-616-8.

Farbotko, C., 2010: 'The global warming clock is ticking so see these places while you can': voyeuristic tourism and model environmental citizens on Tuvalu's disappearing islands. *Singapore Journal of Tropical Geography*, **31(2)**, 224-238.

Faure, M.G. and M. Peeters (eds.), 2011: *Climate Change Liability*. Edward Elgar Publishing, Cheltenham, UK, 304 pp.

Feeley III, T.J., T.J. Skone, G.J. Stiegel Jr, A. McNemar, M. Nemeth, B. Schimmoller, J.T. Murphy, and L. Manfredo, 2008: Water: a critical resource in the thermoelectric power industry. *Energy*, **33(1)**, 1-11.

Feyen, L., R. Dankers, K. Bódis, P. Salamon, and J.I. Barredo, 2012: Fluvial flood risk in Europe in present and future climates. *Climatic Change*, **112(1)**, 47-62.

FHWA, 2006: *Long-Term Pavement Performance (LTPP) Data Analysis Support: National Pooled Fund Study TPF-5(013) – Effects of Multiple Freeze Cycles and Deep Frost Penetration on Pavement Performance and Cost*. Publication No. FHWA-HRT-06-121, U.S. Department of Transportation, Federal Highway Administration (FHWA), Washington, DC, USA, 244 pp.

Fischer, G., T. Francesco, V. Harrij van, and W. David, 2007: Climate change impacts on irrigation water requirements: effects of mitigation, 1990-2080. **74(7)**, 1083-1107.

Ford, J.D., T. Pearce, J. Prno, F. Duerden, L.B. Ford, M. Beaumier, and T. Smith, 2010: Perceptions of climate change risks in primary resource use industries: a survey of the Canadian mining sector. *Regional Environmental Change*, **10(1)**, 65-81.

Ford, J.D., T. Pearce, J. Prno, F. Duerden, L. Berrang Ford, T.R. Smith, and M. Beaumier, 2011: Canary in a coal mine: perceptions of climate change risks and response options among Canadian mine operations. *Climatic Change*, **109(3-4)**, 399-415.

Førland, E.J., J.K. Steen Jacobsen, J.M. Denstadli, M. Lohmann, I. Hanssen-Bauer, H.O. Hygen, and H. Tømmervik, 2012: Cool weather tourism under global warming: comparing Arctic summer tourists' weather preferences with regional climate statistics and projections. *Tourism Management*, **36**, 567-579.

Förster, H. and J. Lilliestam, 2009: Modeling thermoelectric power generation in view of climate change. *Regional Environmental Change*, **10(4)**, 327-338.

Forster, J., P.W. Schuhmann, I.R. Lake, A.R. Watkinson, and J.A. Gill, 2012: The influence of hurricane risk on tourist destination choice in the Caribbean. *Climatic Change*, **114(3-4)**, 745-768.

Furrer, B., J. Hamprecht, and V.H. Hoffmann, 2012: Much Ado about Nothing? How Banks Respond to Climate Change. *Business & Society*, **51(1)**, 62-88.

Füssel, H.-M., 2010: Modeling impacts and adaptation in global IAMs. *Wiley Interdisciplinary Reviews: Climate Change*, **1(2)**, 288-303.

Gabrielsen, K., T. Bye, and F.R. Aune, 2005: *Climate Change-Lower Electricity Prices and Increasing Demand: An Application to the Nordic Countries*. Discussion Paper No. 430, Statistics Norway, Research Department, Kongsvinger, Norway, 34 pp.

Gallup, J.L., J.D. Sachs, and A.D. Mellinger, 1999: Geography and economic development. *International Regional Science Review*, **22(2)**, 179-232.

Galor, O. and D.N. Weil, 1996: The gender gap, fertility, and growth. *American Economic Review*, **86(3)**, 374-387.

GAO, 2010: *National Flood Insurance Program: Continued Actions needed to address Financial and Operational Issues.* GAO-10-1063T, Testimony before the Subcommittee on Housing and Community Opportunity, Committee on Financial Services, House of Representatives, United States Government Accountability Office (GAO), Washington, DC, USA, 22 pp.

GAO, 2011: *Flood Insurance: Public Policy Goals Provide a Framework for Reform.* GAO-11-429T, Testimony before the Subcommittee on Insurance, Housing, and Community Opportunity, Committee on Financial Services, House of Representatives, United States Government Accountability Office (GAO), Washington, DC, USA, 15 pp.

Garnaut, R., 2008: *The Garnaut Climate Change Review: Final Report.* Cambridge University Press, Port Melbourne, Australia, 634 pp.

Garvey, S.D., 2010: Structural capacity and the 20 MW wind turbine. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, **224(8)**, 1083-1115.

Garza-Gil, M.D., J. Torralba-Cano, and M.M. Varela-Lafuente, 2011: Evaluating the economic effects of climate change on the European sardine fishery. *Regional Environmental Change*, **11(1)**, 87-95.

German Insurance Association, 2011: *Auswirkungen des Klimawandels auf die Schadensituation in der deutschen Versicherungswirtschaft. Kurzfassung Hochwasser.* Studie im Auftrag des Gesamtverbandes der Deutschen Versicherungswirtschaft e.V., Produced by Potsdam Institute for Climate Impact Research (PIK), Free University of Berlin (FUB), University of Cologne (Germany), Institute for Applied Water, and Geoinformatics (IAWG) for the German Insurance Association (Gesamtverband der Deutschen Versicherungswirtschaft), GDV, Berlin, Germany, 29 pp.

Gerrard, B.G. (ed.), 2007: *Global Climate Change and U.S. Law*. American Bar Association, Chicago, IL, USA, 784 pp.

Gerstengarbe, F.-W., P.C. Werner, H. Österle, and O. Burghoff, 2013: Winter storm- and summer thunderstorm- related loss events with regard to climate change in Germany. *Theoretical and Applied Climatology*, **114(3-4)**, 715-724, doi:10.1007/s00704-013-0843-y.

Ghesquiere, F. and O. Mahul, 2007: *Sovereign Natural Disaster Insurance for Developing Countries: A Paradigm Shift in Catastrophe Risk Financing*. Policy Research Working Paper, 4345, The World Bank Hazard Risk Management Unit Latin America and Caribbean Region and the Financial Markets for Social Safety Net Department, Financial and Private Sector Development Vice Presidency, The World Bank, Washington, DC, USA, 24 pp.

Giannakopoulos, C., E. Kostopoulou, K.V. Varotsos, K. Tziotziou, and A. Plitharas, 2011: An integrated assessment of climate change impacts for Greece in the near future. *Regional Environmental Change*, **11(4)**, 829-843.

Gibbons, J.H., 2012: Technology and innovation. In: *Energy for Development: Resources*, *Technologies*, *Environment* [Toth, F.L. (ed.)]. Kluwer, Dordrecht, Netherlands, pp. 141-148.

Ginsburgh, V. and M.A. Keyzer, 1997: *The Structure of Applied General Equilibrium Models.* The MIT Press, Cambridge, MA, USA, 555 pp.

Glauber, J.W., 2004: Crop insurance reconsidered. *American Journal of Agricultural Economics*, **86(5)**, 1179-1195.

Gollin, D. and C. Zimmermann, 2008: *Malaria: Disease Impacts and Long-Run Income Differences.* IZA Discussion Paper No. 2997, Forschungsinstitut zur Zukunft der Arbeit Institute for the Study of Labor (IZA), IZA, Bonn, Germany, 25 pp.

Gollin, D. and C. Zimmermann, 2012: Global climate change and the resurgence of tropical disease: an economic approach. *Mathematical Population Studies*, **19(1)**, 51-62.

Golombek, R., S.A.C. Kittelsen, and I. Haddeland, 2011: Climate change: impacts on electricity markets in Western Europe. *Climatic Change*, **113(2)**, 357-370.

Gómez-Martín, M.B., 2006: Climate potential and tourist demand in Catalonia (Spain) during the summer season. *Climate Research*, **32(1)**, 75-87.

Gössling, S. and C.M. Hall, 2006: Uncertainties in predicting tourist flows under scenarios of climate change. *Climatic Change*, **79(3-4)**, 163-173.

Gössling, S., M. Bredberg, A. Randow, E. Sandström, and P. Svensson, 2006: Tourist perceptions of climate change: a study of international tourists in Zanzibar. *Current Issues in Tourism*, **9(4-5)**, 419-435.

Gössling, S., D. Scott, C.M. Hall, J.-P. Ceron, and G. Dubois, 2012: Consumer behaviour and demand response of tourists to climate change. *Annals of Tourism Research*, **39(1)**, 36-58.

Grace, M.F. and R.W. Klein, 2009: The perfect storm: hurricanes, insurance, and regulation. *Risk Management and Insurance Review*, **12(1)**, 81-124.

Graff Zivin, J. and M.J. Neidell, 2010: *Temperature and the Allocation of Time: Implications for Climate Change.* NBER Working Paper 15717, National Bureau of Economic Research (NBER), Washington, DC, USA, 40 pp.

Grey, D. and C.W. Sadoff, 2007: Sink or swim? Water security for growth and development. *Water Policy*, **9(6)**, 545-571.

Guha-Sapir, D., F. Vos, R. Below, and S. Ponserre, 2012: *Annual Disaster Statistical Review 2011: The Numbers and Trends.* Centre for Research on the Epidemiology of Disasters (CRED), Institute of Health and Society (IRSS), Université catholique de Louvain – Brussels, Belgium, 42 pp.

Gusmao, D., 2010: Case-study 2: European airports and sea level rise. In: "*Challenges of Growth" – Environmental Update Study: Climate Adaptation Case Studies* [Thomas, C. and A.J. Drew (eds.)]. European Organisation for the Safety of Air Navigation (EUROCONTROL), Brussels, Belgium, pp. 71-91.

Guy Carpenter, 2011: *Global Reinsurance Outlook, Points of Inflection – Positioning for Change in a Challenging Market.* Guy Carpenter & Company, LLC, New York, NY, USA, 72 pp.

Hall, C.M., 2006: New Zealand tourism entrepreneur attitudes and behaviours with respect to climate change adaptation and mitigation. *International Journal of Innovation and Sustainable Development*, **1(3)**, 229-237.

Hall, J.W., P.B. Sayers, and R.J. Dawson, 2005: National-scale assessment of current and future flood risk in England and Wales. *Natural Hazards*, **36(1-2)**, 147-164.

Hallegatte, S., 2005: The long time scales of the climate-economy feedback and the climatic cost of growth. *Environmental Modeling and Assessment*, **10(4)**, 277-289.

Hallegatte, S. and P. Dumas, 2009: Can natural disasters have positive consequences? Investigating the role of embodied technical change. *Ecological Economics*, **68(3)**, 777-786.

Hallegatte, S. and M. Ghil, 2008: Natural disasters impacting a macroeconomic model with endogenous dynamics. *Ecological Economics*, **68(1-2)**, 582-592.

Hallegatte, S. and D. Thery, 2007: Are the economic impacts of climate change underestimated? *Revue d'Economie Politique*, **117(4)**, 507-522.

Hamilton, J.M., 2007: Coastal landscape and the hedonic price of accommodation. *Ecological Economics*, **62(3-4)**, 594-602.

Hamilton, J.M. and R.S.J. Tol, 2007: The impact of climate change on tourism in Germany, the UK and Ireland: a simulation study. *Regional Environmental Change*, **7(3)**, 161-172.

Hamilton, J.M., D.J. Maddison, and R.S.J. Tol, 2005a: Effects of climate change on international tourism. *Climate Research*, **29(3)**, 245-254.

Hamilton, J.M., D.J. Maddison, and R.S.J. Tol, 2005b: Climate change and international tourism: a simulation study. *Global Environmental Change*, **15(3)**, 253-266.

Hamilton, L.C., C. Brown, and B.D. Keim, 2007: Ski areas, weather and climate: time series models for New England case studies. *International Journal of Climatology*, **27(15)**, 2113-2124.

Hamlet, A.F., S.Y. Lee, K.E.B. Mickelson, and M.M. Elsner, 2010: Effects of projected climate change on energy supply and demand in the Pacific Northwest and Washington State. *Climatic Change*, **102(1-2)**, 103-128.

Hamzah, J., A. Habibah, A. Buang, K. Jusoff, M.E. Toriman, M.J. Mohd. Fuad, A.C. Er, and A.M. Azima, 2012: Flood disaster, impacts and the tourism providers' responses: the Kota Tinggi experience. *Advances in Natural and Applied Sciences*, **6(1)**, 26-32.

Hanewinkel, M., D.A. Cullmann, M.-J. Schelhaas, G.-J. Nabuurs, and N.E. Zimmermann, 2013: Climate change may cause severe loss in the economic value of European forest land. *Nature Climate Change*, **3(3)**, 203-207.

Harrison, S.J., S.J. Winterbottom, and C. Sheppard, 1999: The potential effects of climate change on the Scottish tourist industry. *Tourism Management*, **20(2)**, 203-211.

Haug, O., X.K. Dimakos, J.F. Vardal, M. Aldrin, and E. Meze-Hausken, 2011: Future building water loss projections posed by climate change. *Scandinavian Actuarial Journal*, **2011(1)**, 1-20, doi:10.1080/03461230903266533.

Haugen, J.E. and T. Iversen, 2008: Response in extremes of daily precipitation and wind from a downscaled multi- model ensemble of anthropogenic global climate change scenarios. *Tellus A*, **60(3)**, 411-426.

Hecht, S.B., 2008: Climate change and the transformation of risk: insurance matters. *UCLA Law Review*, **55**, 1559-1620.

Hein, L., M.J. Metzger, and A. Moreno, 2009: Potential impacts of climate change on tourism: a case study for Spain. *Current Opinion in Environmental Sustainability*, **1(2)**, 170-178.

Heintz, J.E., M.H. Kanemitsu, and E. Scanlan, 2009: Insurance coverage for climate change suits: the battle has begun. *Environmental Claims Journal*, **21(1)**, 29-51.

Held, H., F.-W. Gerstengarbe, T. Pardowitz, J.F. Pinto, U. Ulbrich, K. Born, M.G. Donat, M.K. Karremann, G.C. Leckebusch, P. Ludwig, K.M. Nissen, H. Österle, B.F. Prahl, P.C. Werner, D.J. Befort, and O. Burghoff, 2013: Projections of global warming-induced impacts on winter storm losses in the German private household sector. *Climatic Change*, **121(2)**, 195-207.

Henderson, J., C. Rodgers, R. Jones, J. Smith, K. Strzepek, and J. Martinich, 2013: Economic impacts of climate change on water resources in the coterminous United States. *Mitigation and Adaptation Strategies for Global Change*, doi:10.1007/s11027-013-9483-x.

Hendrikx, J. and E.Ö. Hreinsson, 2012: The potential impact of climate change on seasonal snow in New Zealand: part II – industry vulnerability and future snow-making potential. *Theoretical and Applied Climatology*, **110(4)**, 619-630.

Hendrikx, J., E.Ö. Hreinsson, M.P. Clark, and A.B. Mullan, 2012: The potential impact of climate change on seasonal snow in New Zealand: part I – an analysis using 12 GCMs. *Theoretical and Applied Climatology*, **110(4)**, 607-618.

Hendrikx, J., C. Zammit, E.Ö. Hreinsson, and S. Becken, 2013: A comparative assessment of the potential impact of climate change on the ski industry in New Zealand and Australia. *Climatic Change*, **119(3-4)**, 965-978.

Herbold, J., 2013a: New approaches to agricultural insurance in developing economies. In: *Finance for Food: Towards New Agricultural and Rural Finance* [Köhn, D. (ed.)]. Kreditanstalt für Wiederaufbau (KfW), Springer, Heidelberg, Gemany (in press).

Herbold, J., 2013b: Index insurance in agriculture – the (re)insurer's perspective. In: *The Challenges of Index-Based Insurance for Food Security in Developing Countries* [Gommes, R. and F. Kayitakire (eds.)]. Proceedings of a technical workshop organised by the EC Joint Research Centre (JRC) and the International Research Institute for Climate and Society (IRI, Earth Institute, Columbia University), JRC Ispra, Italy, 2 and 3 May 2012, European Union Publication Office, Luxembourg, Luxembourg, pp. 47-54.

Hertin, J., F. Berkhout, D.M. Gann, and J. Barlow, 2003: Climate change and the UK house building sector: perceptions, impacts and adaptive capacity. *Building Research and Information*, **31(3-4)**, 278-290.

Herweijer, C., N. Ranger, and R.E.T. Ward, 2009: Adaptation to climate change: threats and opportunities for the insurance industry. *The Geneva Papers*, **34**, 360-380.

Hess, U. and P. Hazell, 2009: Sustainability and scalability of index-based insurance for agriculture. In: *Innovations in Insuring the Poor* [Vargas Hill, R. and M. Torrero (eds.)]. The International Food Policy Research Institute (IFPRI), Washington, DC, USA, pp. 13-14.

Hess, J.J., K.L. Heilpern, T.E. Davis, and H. Frumkin, 2009: Climate change and emergency medicine: impacts and opportunities. *Academic Emergency Medicine*, **16(8)**, 782-794.

Hill, M., A. Wallner, and J. Furtado, 2010: Reducing vulnerability to climate change in the Swiss Alps: a study of adaptive planning. *Climate Policy*, **10(1)**, 70-86.

Hilmi, N., D. Allemand, S. Dupont, A. Safa, G. Haraldsson, P.A.L.D. Nunes, C. Moore, C. Hattam, S. Reynaud, J.M. Hall-Spencer, M. Fine, C. Turley, R. Jeffree, J. Orr, P.L. Munday, and S.R. Cooley, 2013: Towards improved socio-economic assessments of ocean acidification's impacts. *Marine Biology*, **160(8)**, 1773-1787.

Hines, P., J. Apt, and S. Talukdar, 2009: Large blackouts in North America: historical trends and policy implications. *Energy Policy*, **37(12)**, 5249-5259.

Hochrainer, S., R. Mechler, and D. Kull, 2010: Micro-insurance against drought risk in changing climate. Assessing demand and supply considerations. *International Journal of Climate Strategies and Management*, **2(2)**, 148-166.

Hochrainer, S. and R. Mechler, 2011: Natural disaster risk in Asian megacities: a case for risk pooling? *Cities*, **28**, 53-61.

Hoffmann, B., U. Müller, S. Häfele, and U. Karl, 2010: Analysis of the impact of changing hydro-meteorological parameters on the electricity production of once-through cooled thermal power plants in Germany – a System Dynamics modelling approach. In: *Proceedings of the International Conference on Energy, Environment and Health – Optimisation of Future Energy Systems* [Siggaard-Andersen, M.-L. and E. Kaas (eds.)]. CEEH Scientific Report No. 9, July, 2011, Proceedings of the conference at Carlsberg Academy, Copenhagen, Denmark, May 31 -June 2, 2010, organized by the Centre for Energy Environment and Health (CEEH), the REBECa project (Renewable Energy in the transport sector - using Biofuels as Energy Carriers), and the CEESA project (Coherent Energy and Environmental System Analysis), CEEH, Earth and Planetary Science, University of Copenhagen, Copenhagen, Denmark, pp. 36-42.

Hoffmann, V.H., D.C. Sprengel, A. Ziegler, M. Kolb, and B. Abegg, 2009: Determinants of corporate adaptation to climate change in winter tourism: an econometric analysis. *Global Environmental Change*, **19(2)**, 256-264.

Honeyborne, R., 2009: *Flat Plate versus Evacuated Tube Solar Collectors.* International Technology Sourcing (ITS), Solar Division, ITS Solar, Cape Town, South Africa.

Hope, C.W., 2013: Critical issues for the calculation of the social cost of CO_2: why the estimates from PAGE09 are higher than those from PAGE2002. *Climatic Change*, **117**, 531-543.

Hope, C.W. and M. Hope, 2013: The social cost of CO_2 in a low-growth world. *Nature Climate Change*, **3**, 722-724.

Hopkins, D., J.E.S. Higham, and S. Becken, 2012: Climate change in a regional context: relative vulnerability in the Australasian skier market. *Regional Environmental Change*, **13(2)**, 449-458.

Horowitz, J.K., 2009: The income-temperature relationship in a cross-section of countries and its implications for predicting the effects of global warming. *Environmental and Resource Economics*, **44(4)**, 475-493.

Hsiang, S.M., 2010: Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America. *Proceedings of the National Academy of Sciences of the United States of America*, **107(35)**, 15367-15372.

Hübler, M., G. Klepper, and S. Peterson, 2008: Costs of climate change. The effects of rising temperatures on health and productivity in Germany. *Ecological Economics*, **68(1-2)**, 381-393.

Huebner, A., 2012: Public perceptions of destination vulnerability to climate change and implications for long-haul travel decisions to small island states. *Journal of Sustainable Tourism*, **20(7)**, 939-951.

Hughes, G., P. Chinowsky, and K. Strzepek, 2010: The costs of adaptation to climate change for water infrastructure in OECD countries. *Utilities Policy*, **18(3)**, 142-153.

Hunt, A. and P. Watkiss, 2010: Climatic change impacts and adaptation in cities: a review of the literature. *Climatic Change*, **104(1)**, 13-49.

Hurd, B. and M. Rouhi-Rad, 2013: Estimating economic effects of changes in climate and water availability. *Climatic Change*, **117(3)**, 575-584.

Hurd, B.H., M. Callaway, J. Smith, and P. Kirshen, 2004: Climatic change and U.S. water resources: from modeled watershed impacts to national estimates. *Journal of the American Water Resource Association*, **40(1)**, 129-148.

Hutton, G., 2011: The economics of health and climate change: key evidence for decision making. *Globalization and Health*, **7(18)**, doi:10.1186/1744-8603-7-18.

Hwang, I.C., F. Reynès, and R.S.J. Tol, 2013: Climate policy under fat-tailed risk: an application of Dice. *Environmental and Resource Economics*, **56**, 415-436, doi:10.1007/s10640-013-9654-y .

IAEA, 2011: *Core Knowledge on Instrumentation and Control Systems in Nuclear Power Plants.* IAEA Nuclear Energy Series No. NP-T-3.12, International Atomic Energy Agency (IAEA), Vienna, Austria, 141 pp.

Ibarra, E.M., 2011: The use of webcam images to determine tourist-climate aptitude: favourable weather types for sun and beach tourism on the Alicante coast (Spain). *International Journal of Biometeorology*, **55(3)**, 373-385.

IEA, 2008: *World Energy Outlook 2008.* Organization for Economic Cooperation and Development (OECD) and International Energy Agency (IEA), Paris, France, 569 pp.

IEA, 2009: *World Energy Outlook 2009.* Organization for Economic Cooperation and Development (OECD) and International Energy Agency (IEA), Paris, France, 691 pp.

IEA, 2010a: *World Energy Outlook 2010.* Organization for Economic Cooperation and Development (OECD) and International Energy Agency (IEA), Paris, France, 731 pp.

IEA, 2010b: *Energy Technology Perspectives 2010.* Organization for Economic Cooperation and Development (OECD) and International Energy Agency (IEA), Paris, France, 706 pp.

IEA, 2012: *World Energy Outlook 2012.* Organization for Economic Cooperation and Development (OECD) and International Energy Agency (IEA), Paris, France, 668 pp.

Iizumi, T., M. Yokozawa, Y. Hayashi, and F. Kimura, 2008: Climate change impact on rice insurance payouts in Japan. *Journal of Applied Meteorology and Climatology*, **47**, 2265-2278.

Ikefuji, M., J. Magnus, and H. Sakamoto, 2010: *Climate Change, Economic Growth, and Health.* Discussion Paper No. 2010-86, Tilburg University Center for Economic Research, Amsterdam, Netherland, 39 pp.

Ikefuji, M. and R. Horii, 2012: Natural disasters in a two-sector model of endogenous growth. *Journal of Public Economics*, **96(9-10)**, 784-796.

Interagency Working Group on the Social Cost of Carbon, 2010: *Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866.* February, 2010, The Interagency Working Group (IAW) on the Social Cost of Carbon (SCC), United States Government, Washington, DC, USA, 51 pp.

Interagency Working Group on the Social Cost of Carbon, 2013: *Technical Support Document – Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis – under Executive Order 12866.* The Interagency Working Group (IAW) on the Social Cost of Carbon (SCC), United States Government, Washington, DC, USA, 21 pp.

IPCC, 2005: *IPCC Special Report on Carbon Dioxide Capture and Storage.* Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H.C. de Coninck, M. Loos, and L.A. Meyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 442 pp.

IPCC, 2011: *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation.* Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, and C. von Stechow (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1075 pp.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp.

Isaac, M. and D. Van Vuuren, 2009: Modelling global residential sector energy demand for heating and air conditioning in the context of climate change. *Energy Policy*, **37**, 507-521.

Jiang, M., E. Wong, L.M. Klint, T. DeLacy, and D. Dominey-Howes, 2012: Tourism adaptation to climate change –analysing the policy environment of Fiji. *International Journal of Tourism Policy*, **4(3)**, 238-260.

Jochem, E.S., T. Barker, G. Catenazzi, W. Eichhammer, T. Fleiter, A. Held, N. Helfrich, M. Jakob, P. Criqui, S. Mima, L. Quandt, A. Peters , M. Ragwitz, U. Reiter, F. Reitze, M. Schelhaas, S. Scrieciu, and H. Turton, 2009: *Report of the Reference and 2°C Scenario for Europe.* Project No. 018476-GOCE, Deliverable D-M1.2 of the ADAM project (Adaptation and Mitigation Strategies: Supporting European Climate Policy), Fraunhofer Institute for Systems and Innovation Research (ISI), Karlsruhe, Germany, 231 pp.

Jones, B.F. and B.A. Olken, 2010: Climate shocks and exports. *American Economic Review*, **100(2)**, 454-459.

Jones, B., D. Scott, and H.A. Khaled, 2006: Implications of climate change for outdoor event planning: a case study of three special events in Canada's National Capital Region. *Event Management*, **10(1)**, 63-76.

Jopp, R., T. DeLacy, J. Mair, and M. Fluker, 2013: Using a regional tourism adaptation framework to determine climate change adaptation options for Victoria's Surf Coast. *Asia Pacific Journal of Tourism Research*, **18(1-2)**, 144-164.

Jorgenson, D., R. Goettle, B. Hurd, and J. and Smith, 2004: *U.S. Market Consequences of Global Climate Change.* Pew Center on Global Climate Change, Arlington, VA, USA, 44 pp.

Kabat, P., H. van Schaik, and B. Appleton, 2003: *Climate Changes the Water Rules: How Water Managers can cope with Today's Climate Variability and Tomorrow's Climate Change.* Dialogue on Water and Climate (DWC), International Secretariat of DWC, Wageningen, Netherlands, 105 pp.

Kane, S., J.M. Reilly, and J. Tobey, 1992: An empirical study of the economic effects of climate change on world agriculture. *Climatic Change*, **21(1)**, 17-35.

Karl, T.R., J.M. Melillo, and T.C. Peterson (eds.), 2009: *Global Climate Change Impacts in the United States.* State of the Knowledge Report by the U.S. Global Change Research Program, Cambridge University Press, New York, NY, USA, 188 pp.

Kemfert, C., 2002: An integrated assessment model of economy-energy-climate – the Model WIAGEM. *Integrated Assessment*, **3(4)**, 281-298.

Khosla, V., 2008: *Scalable Electric Power from Solar Energy.* Breaking the Climate Deadlock Briefing Paper, The Climate Group, Brussels, Belgium, 19 pp.

Kingwell, R. and I. Farré, 2009: Climate change impacts on investment in crop sowing machinery. *Australian Journal of Agricultural and Resource Economics*, **53(2)**, 265-284.

Kirkinen, J., A. Martikainen, H. Holttinen, I. Savolainen, O. Auvinen, and S. Syri, 2005: *Impacts on the Energy Sector and Adaptation of the Electricity Network Business under a Changing Climate in Finland*. Finnish Environment Institute (SKYE) Mimeographs No. 340, FINADAPT Working Paper 10, FINADAPT Consortium co-ordinated at SYKE as a part of the Finnish Environmental Cluster Research Programme, co-ordinated by the Finnish Ministry of the Environment, Helsinki, Finland, 36 pp.

Kirshen, P., M. Ruth, and W. Anderson, 2006: Climate's long-term impacts on urban infrastructures and services: the case of Metro Boston. In: *Regional Climate Change and Variability: Impacts and Responses* [Ruth, M., K. Donaghy, and P. Kirshen (eds.)]. New Horizons in Regional Science Series, Edward Elgar Publishers, Northampton, MA, USA, pp. 190-252.

Kirshen, P., K. Knee, and M. Ruth, 2008a: Climate change and coastal flooding in Metro Boston: impacts and adaptation strategies. *Climatic Change*, **90(4)**, 453-473.

Kirshen, P., M. Ruth, and W. Anderson, 2008b: Interdependencies of urban climate change impacts and adaptation strategies: a case study of Metropolitan Boston USA. *Climatic Change*, **86(1-2)**, 105-122.

Kjellstrom, T., R.S. Kovats, S.J. Lloyd, T. Holt, and R.S. Tol, 2009: The direct impact of climate change on regional labor productivity. *Archives of Environmental & Occupational Health*, **64(4)**, 217-227.

Kjellstrom, T., B. Lemke, and M. Otto, 2013: Mapping occupational heat exposure and effects in South-East Asia: ongoing time trends 1980-2009 and future estimates to 2050. *Industrial Health*, **51**, 56-67.

Klint, L.M., M. Jiang, A. Law, T. DeLacy, S. Filep, E. Calgaro, D. Dominey-Howes, and D. Harrison, 2012: Dive tourism in Luganville, Vanuatu: shocks, stressors, and vulnerability to climate change. *Tourism in Marine Environments*, **8(1-2)**, 91-109.

Knowlton, K., M. Rotkin-Ellman, L. Geballe, W. Max, and M.S. Gina, 2011: Six climate change-related events in the United States accounted for about $14 billion in lost lives and health costs. *Health Affairs*, **30(11)**, 2167-2176.

Koch, H., S. Vögele, M. Kaltofen, and U. Grünewald, 2012: Trends in Water availability for power plants-scenario analyses for the German Capital Berlin. *Climatic Change*, **110(3-4)**, 879-899.

Koetse, M. and P. Rietveld, 2009: The impact of climate change and weather on transport: an overview of empirical findings. *Transportation Research Part D: Transport and Environment*, **14(3)**, 205-221.

Kong, C., J. Bang, and Y. Sugiyama, 2005: Structural investigation of composite wind turbine blade considering various load cases and fatigue life. *Energy*, **30**, 2101-2114.

Kopp, R.E., A. Golub, N.O. Keohane, and C. Onda, 2012: The influence of the specification of climate change damages on the social cost of carbon. *Economics: The Open-Access, Open-Assessment E-Journal*, **6**, 2012-13, doi:10.5018/economics-ejournal.ja.2012-13.

Kousky, C. and R. Cooke, 2012: Explaining the failure to insure catastrophic risks. *The Geneva Papers*, **37(2)**, 206-227, doi:10.1057/gpp.2012.14.

Kousky, C. and H. Kunreuther, 2010: Improving flood insurance and flood-risk management: insights from St. Louis, Missouri. *Natural Hazards Review*, **11(4)**, 162-172.

Krausmann, E. and F. Mushtaq, 2008: A qualitative Natech damage scale for the impact of floods on selected industrial facilities. *Natural Hazards*, **46(2)**, 179-197.

Krekt, A.H., T.J. van der Laan, R.A.E. van der Meer, B. Turpin, O.E. Jonkeren, A. van der Toorn, E. Mosselman, J. van Meijeren, and T. Groen, 2011: *Climate Change and Inland Waterway Transport: Impacts on the Sector, the Port of Rotterdam and Potential Solutions.* Research Project HSRR08, National Research Programme Knowledge for Climate, Secretariat of the Knowledge for Climate Programme, University of Utrecht, Utrecht, Netherlands, 74 pp.

Kron, W., 2009: Flood insurance: from clients to global financial markets. *Journal of Flood Risk Management*, **2**, 68-75, doi:10.1111/j.1753-318X.2008.01015.x.

Kron, W., 2012: Changing flood risk – a re-insurer's viewpoint. In: *Changes in Flood Risk in Europe* [Kundzewicz, Z.W. (ed.)]. International Association of Hydrological Sciences, Wallingford, UK, pp. 459-490.

Kron, W. and G. Berz, 2007: Flood disasters and climate change: trends and options – a (re-)insurer's view. In: *Global Change: Enough Water for All?* [Lozán, J.L., H. Graßl, P. Hupfer, L. Menzel, and C.-D. Schönwiese (eds.). Wissenschaftliche Auswertungen, Hamburg, Germany, pp. 268-273.

Kron, W., M. Steuer, P. Loew, and A. Wirtz, 2012: How to deal properly with a natural catastrophe database – analysis of flood losses. *Natural Hazards and Earth System Sciences*, **12**, 535-550.

Kulshreshtha, S.N., 2011: Climate change, prairie agriculture, and prairie economy: the new normal. *Canadian Journal of Agricultural Economics*, **59(1)**, 19-44.

Kundzewicz, Z.W., L.J. Mata, N.W. Arnell, P. Döll, P. Kabat, B. Jiménez, K.A. Miller, T. Oki, Z. Sen and I.A. Shiklomanov , 2007: Freshwater resources and their management. In: *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Metz, B., O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 173-210.

Kunreuther, H.C. and E.O. Michel-Kerjan, 2009: The development of new catastrophe risk markets. *Annual Review of Resource Economics*, **1**, 119-139.

Kunreuther, H.C., E.O. Michel-Kerjan, N.A. Doherty, M.R. Grace, R.W. Klein, and M.V. Pauly, 2009: *At War with the Weather: Managing Large-Scale Risks in a New Era of Catastrophes.* The Massachusetts Institute of Technology (MIT) Press, Cambridge, MA, USA and London, UK, pp. 416.

Kunreuther, H.C., E.O. Michel-Kerjan, and N. Ranger, 2012: Insuring future climate catastrophes. *Climatic Change*, **118(2)**, 339-354.

Kunz, K., J. Sander, and C. Kottmeier, 2009: Recent trends of thunderstorm and hailstorm frequency and their relation to atmospheric characteristics in southwest Germany. *International Journal of Climatology*, **29**, 2283-2297.

Kurtz, S., J. Granata, and M. Quintana, 2009: Photovoltaic reliability R&D toward a solar-powered world. In: *Proceedings of SPIE: Reliability of Photovoltaic Cells, Modules, Components, and Systems II* [Dhere, N.G., J.H. Wohlgemuth, and D.T. Ton (eds.)]. Proceedings of the International Society for Optics and Photonics (SPIE), Vol. 7412, SPIE, Bellingham, WA, USA, Article No. 7412 0Z, doi:10.1117/12.825649.

Kurtz, S., K. Whitfield, G. TamizhMani, M. Koehl, D. Miller, J. Joyce, J. Wohlgemuth, N. Bosco, M. Kempe, and T. Zgonena, 2011: Evaluation of high temperature exposure of photovoltaic modules. *Progress in Photovoltaics: Research and Applications*, **19(8)**, 954-965.

Landauer, M., U. Pröbstl, and W. Haider, 2012: Managing cross-country skiing destinations under the conditions of climate change – scenarios for destinations in Austria and Finland. *Tourism Management*, **33(4)**, 741-751.

Larsen, P., S. Goldsmith, O. Smith, M. Wilson, K. Strezpek, P. Chinowsky, and B. Saylor, 2008: Estimating future costs for Alaska public infrastructure at risk from climate change. *Global Environmental Change*, **18**, 442-457.

Lavin, P.G., 2003: *Asphalt Pavements: A Practical Guide to Design, Production, and Maintenance for Architects and Engineers*. Spon Press, London, UK and New York, NY, USA, 444 pp.

Le Floc'h, P., J.-C. Poulard, O. Thébaud, F. Blanchard, J. Bihel, and F. Steinmetz, 2008: Analyzing the market position of fish species subject to the impact of long-term changes: a case study of French fisheries in the Bay of Biscay. *Aquatic Living Resources*, **21(3)**, 307-316.

Leblois, A. and P. Quirion, 2013: Agricultural insurances based on meteorological indices: realizations, methods and research challenges. *Meteorological Applications*, **20(1)**, 1-9, doi:10.1002/met.303.

Leckebusch, G.C., U. Ulbrich, L. Fröhlich, and J.G. Pinto, 2007: Property loss potentials for European midlatitude storms in a changing climate. *Geophysical Research Letters*, **34(5)**, doi:10.1029/2006GL027663.

Leckebusch, G.C., A. Weimer, J.G. Pinto, M. Reyers, and P. Speth, 2008: Extreme wind storms over Europe in present and future climate: a cluster analysis approach. *Meteorologische Zeitschrift*, **17(1)**, 67-82.

Lee, D.M. and K.S. Lyon, 2004: A dynamic analysis of the global timber market under global warming: an integrated modeling approach. *Southern Economic Journal*, **70(3)**, 467-489.

Lee, H.-L., 2009: The impact of climate change on global food supply and demand, food prices, and land use. *Paddy and Water Environment*, **7(4)**, 321-331.

Leiva, A.J. and J.R. Skees, 2008: Using irrigation insurance to improve water usage of the Rio Mayo irrigation system in Northwestern Mexico. *World Development*, **36(12)**, 2663-2678.

Lemmen, D. and F. Warren, 2010: *Climate Change Impacts and Adaptation: A Canadian Perspective* [Lemmen, D. and F. Warren (eds.)]. Government of Canada, Climate Change Impacts and Adaptation Directorate, Natural Resources Canada, Ottawa, ON, Canada, 174 pp.

Lin, S., H. Wan-Hsiang, V.Z. Alissa, S. Shubhayu, L. George, and H. Syni-An, 2012: Excessive heat and respiratory hospitalizations in New York State: estimating current and future public health burden related to climate change. *Environmental Health Perspectives*, **120(12)**, 1571-1577, doi: 10.1289/ehp.1104728.

Lin, T.-P. and A. Matzarakis, 2008: Tourism climate and thermal comfort in Sun Moon Lake, Taiwan. *International Journal of Biometeorology*, **52(4)**, 281-290.

Lin, T.-P. and A. Matzarakis, 2011: Tourism climate information based on human thermal perception in Taiwan and Eastern China. *Tourism Management*, **32(3)**, 492-500.

Link, P.M. and R.S.J. Tol, 2009: Economic impacts on key Barents Sea fisheries arising from changes in the strength of the Atlantic thermohaline circulation. *Global Environmental Change*, **19(4)**, 422-433.

Linnerooth-Bayer, J. and R. Mechler, 2009: *Insurance against Losses from Natural Disasters in Developing Countries.* DESA Working Paper No. 85, ST/ESA/2009/DWP/85, United Nations Department of Economic and Social Affairs (UN DESA), New York, NY, USA, 35 pp.

Linnerooth-Bayer, J., K. Warner, C. Bals, P. Höppe, I. Burton, T. Loster, and A. Haas, 2009: Insurance, developing countries and climate change. *The Geneva Papers*, **34**, 381-400.

Linnerooth-Bayer, J., R. Mechler, and S. Hochrainer-Stigler, 2011: Insurance against losses from natural disasters in developing countries – evidence, gaps and the way forward. *Journal of Integrated Disaster Risk Management*, **1(1)**, 59-81, doi:10.5595/idrim.2011.0013.

Linnerud, K., T.K. Mideksa, and G.S. Eskeland, 2011: The impact of climate change on nuclear power supply. *Energy Journal*, **32(1)**, 149-168.

Lise, W. and R.S.J. Tol, 2002: Impact of climate on tourist demand. *Climatic Change*, **55(4)**, 429-449.

Lo, A.J., 2013: The likelihood of having flood insurance increases with social expectations. *Area*, **45(1)**, 70-76.

Lu, C., M.T. Schneider, P. Gubbins, K. Leach-Kemon, D. Jamison, and C.J. Murray, 2010: Public financing of health in developing countries: a cross-national systematic analysis. *The Lancet*, **375(9723)**, 1375-1387.

Macknick, J., R. Newmark, G. Heath, and K.C. Hallett, 2011: *A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies*. Technical Report NREL/TP-6A20-50900. National Renewable Energy Laboratory, Golden, CO, USA, 21 pp. http://www.nrel.gov/docs/fy11osti/50900.pdf.

Maddison, D., 2001: In search of warmer climates? The impact of climate change on flows of British tourists. *Climatic Change*, **49(1-2)**, 193-208.

Maddison, D. and K. Rehdanz, 2011: The impact of climate on life satisfaction. *Ecological Economics*, **70(12)**, 2437-2445.

Mahul, O. and C.J. Stutley, 2010: *Government Support to Agricultural Insurance: Challenges and Options for Developing Countries.* The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 219 pp.

Makki, S.S. and A. Somwaru, 2001: Evidence of adverse selection in crop insurance markets. *The Journal of Risk and Insurance*, **68(4)**, 685-708.

Mansur, E.T., R.O. Mendelsohn, and W. Morrison, 2005: *A Discrete-Continuous Choice Model of Climate Change Impacts on Energy*. Yale SOM Working Paper ES-43, Yale School of Management and School of Forestry and Environmental Studies, New Haven, CT, USA, 45 pp.

Markandya, A. and A. Chaibai, 2009: Valuing climate change impacts on human health: empirical evidence from the literature. *International Journal of Environmental Resources and Public Health*, **6**, 759-786.

Markoff, M.S. and A.C. Cullen, 2008: Impact of climate change on Pacific northwest hydropower. *Climatic Change*, **87**, 451-469.

Masters, W.A. and M.S. McMillan, 2001: Climate and scale in economic growth. *Journal of Economic Growth*, **6(3)**, 167-186.

Matzarakis, A. and C. Endler, 2010: Climate change and thermal bioclimate in cities: impacts and options for adaptation in Freiburg, Germany. *International Journal of Biometeorology*, **54(4)**, 479-483.

Matzarakis, A., T. Georgiadis, and F. Rossi, 2007: Thermal bioclimate analysis for Europe and Italy. *Il Nuovo Cimento*, **30(6)**, 623-632, doi:10.1393/ncc/i2007-10268-0.

Matzarakis, A., E. Rudel, M. Zygmuntowski, and E. Koch, 2010: Bioclimatic maps for tourism purposes. *Physics and Chemistry of the Earth*, **35(1-2)**, 57-62.

Matzarakis, A., M. Hämmerle, C. Endler, S. Muthers, and E. Koch, 2012: Assessment of tourism and recreation destinations under climate change conditions in Austria. *Meteorologische Zeitschrift*, **21(2)**, 157-165.

Maynard, T. and N. Ranger, 2012: What role for "long-term insurance" in adaptation? An analysis of the prospects for and pricing of multi-year insurance contracts. *The Geneva Papers*, **37(2)**, 318-339.

McBoyle, G., D. Scott, and B. Jones, 2007: Climate change and the future of snowmobiling in non-mountainous regions of Canada. *Managing Leisure*, **12(4)**, 237-250.

McColl, L., 2012: *Assessing the Potential Impact of Climate Change on the UK's Electricity Network*. Met Office, Exeter, UK, 2 pp.

McDermott, G. and O. Nilsen, 2013: *Electricity Prices, River Temperatures and Cooling Water Scarcity.* IZA Discussion Paper No. 6482, Institute for the Study of Labour (IZA), Bonn, Germany, 38 pp.

McGoodwin, J.R., 2007: Effects of climatic variability on three fishing economies in high-latitude regions: implications for fisheries policies. *Marine Policy*, **31(1)**, 40-55.

McIlgorm, A., 2010: Economic impacts of climate change on sustainable tuna and billfish management: insights from the Western Pacific. *Progress in Oceanography*, **86(1-2)**, 187-191.

Mechler, R., J. Linnerooth-Bayer, and D. Peppiatt, 2006: *Disaster Insurance for the Poor? A Review of Microinsurance for Natural Disaster Risks in Developing Countries.* ProVention Consortium and International Institute for Applied Systems Analysis (IIASA) Study, ProVention, Geneva, Switzerland and IIASA, Laxenburg, Austria, 31 pp.

Melecky, M. and C. Raddatz, 2011: *How Do Governments Respond after Catastrophes? Natural-Disaster Shocks and the Fiscal Stance*. Policy Research Working Paper No. 5564, The World Bank, Private & Financial Sectors Development Sector Unit, Europe and Central Asia Region, Washington, DC, USA, 25 pp.

Mendelsohn, R., K. Emanuel, S. Chonabayashi, and L. Bakkensen, 2012: The impact of climate change on global tropical cyclone damage. *Nature Climate Change*, **2**, 205-209.

Mendoza, R.U., 2009: A proposal for an Asian rice insurance mechanism. *Global Economy Journal*, **9(1)**, 6, doi:10.2202/1524-5861.1454.

Mercer, 2011: *Climate Change Scenarios – Implications for Strategic Asset Allocation.* Mercer, LLC, Carbon Trust, UK, and International Finance Corporation (IFC), Mercer, LLC, New York, NY, USA, 124 pp.

Merino, G., M. Barange, and C. Mullon, 2010: Climate variability and change scenarios for a marine commodity: modelling small pelagic fish, fisheries and fishmeal in a globalized market. *Journal of Marine Systems*, **81(1-2)**, 196-205.

Meze-Hausken, E., A. Patt, and S. Fritz, 2009: Reducing climate risk for micro-insurance providers in Africa: a case study of Ethiopia. *Global Environmental Change*, **19**, 66-73.

Michel-Kerjan, E.O., 2010: Catastrophe economics: the national flood insurance program. *Journal of Economic Perspectives*, **24(4)**, 165-186.

Michel-Kerjan, E. and H. Kunreuther, 2011: Redesigning flood insurance. *Science*, **333**, 408-409.

Michel-Kerjan, E. and F. Morlaye, 2008: Extreme events, global warming, and insurance-linked securities: how to trigger the tipping point. *The Geneva Papers*, **33**, 153-176.

Michel-Kerjan, E., S. Hochrainer-Stigler, H. Kunreuther, H. Kunreuther, J. Linnerooth-Bayer, R. Mechler, R. Muir-Wood, N. Ranger, P. Vaziri, and M. Young, 2013: Catastrophe risk models for evaluating disaster risk reduction investments in developing countries. *Risk Analysis*, **33(6)**, 984-999.

Middelkoop, H., K. Daamen, D. Gellens, W. Grabs, J.C.J. Kwadijk, H. Lang, B.W.A.H. Parmet, B. Schädler, J. Schulla, and K. Wilke, 2001: Impact of climate change on hydrological regimes and water resources management in the Rhine basin. *Climatic Change*, **49(1-2)**, 105-128.

Mideksa, T.K. and S. Kallbekken, 2010: The impact of climate change on the electricity market: a review. *Energy Policy*, **38(7)**, 3579-3585.

Mika, J., 2013: Changes in weather and climate extremes: phenomenology and empirical approaches. *Climatic Change*, **121(1)**, 15-26.

Millerd, F., 2010: The potential impacts of climate change on Great Lakes international shipping. *Climatic Change*, **104(3-4)**, 629-652.

Millner, A., 2013: On welfare frameworks and catastrophic climate risks. *Journal of Environmental Economics and Management*, **65(2)**, 310-325.

Mills, B.N. and J. Andrey, 2002: Climate change and transportation: potential interactions and impacts. In: *The Potential Impacts of Climate Change on Transportation*. Federal Research Partnership Workshop October 1-2, 2002, held at the Brookings Institution, Washington, DC, USA, Summary and Discussion Papers, U.S. Department of Transportation Center for Climate Change and Environmental Forecasting (DOT), Washington, DC, USA, pp. 77-88.

Mills, E., 2009: A global review of insurance industry responses to climate change. *The Geneva Papers*, **34**, 323-359.

Mills, E., 2012: The Greening of insurance. *Science*, **338**, 1424-1425.

Moen, J. and P. Fredman, 2007: Effects of climate change on alpine skiing in Sweden. *Journal of Sustainable Tourism*, **15(4)**, 418-437.

Mogaka, H., S. Gichere, and R. Davis, 2006: *Climate Variability and Water Resources Degradation in Kenya: Improving Water Resources Development and Management.* World Bank Working Paper No. 69, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 105 pp.

Moiseyev, A., B. Solberg, A.M.I. Kallio, and M. Lindner, 2011: An economic analysis of the potential contribution of forest biomass to the EU RES target and its implications for the EU forest industries. *Journal of Forest Economics*, **17(2)**, 197-213.

Monti, A., 2012: Public-private initiatives to cover extreme events. In: *The Geneva Reports – Risk and Insurance Research No.5. Extreme Events and Insurance: 2011 annus horribilis* [Courbage, C. and W.R. Stahel (eds.)]. The Geneva Association, The International Association for the Study of Insurance Economics, Geneva, Switzerland, pp. 27-38.

Moreno, A., 2010: Mediterranean tourism and climate (change): a survey-based study. *Tourism and Hospitality, Planning and Development*, **7(3)**, 253-265.

Moreno, A., B. Amelung, and L. Santamarta, 2008: Linking beach recreation to weather conditions: a case study in Zandvoort, Netherlands. *Tourism in Marine Environments*, **5(2-3)**, 111-119.

Moreno, A. and B. Amelung, 2009: Climate change and tourist comfort on Europe's beaches in summer: a reassessment. *Coastal Management*, **37(6)**, 550-568.

Morrison, C. and C. Pickering, 2012: Limits to climate change adaptation: case study of the Australian Alps. *Geographical Research*, **51(1)**, 11-25.

Muir-Wood, R. and P. Grossi, 2008: The catastrophe modeling response to Hurricane Katrina. In: *Climate Extremes and Society* [Diaz, H.F. and R.J. Murnane (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 296-319.

Mukheibir, P., 2013: Potential consequences of projected climate change impacts on hydroelectricity generation. *Climatic Change*, **121(1)**, 67-78.

Muller, M., 2007: Adapting to climate change: water management for urban resilience. *Environment and Urbanization*, **19(1)**, 99-113.

Munich Re, 2005: *Weather Catastrophes and Climate Change: Is There Still Hope for Us?* Münchener Rückversicherungs-Gesellschaft, Munich Reinsurance Company (Munich Re), Munich, Germany, 264 pp.

Munich Re, 2011: *Topics Geo: Natural Catastrophes 2010: Analyses, Assessments, Positions.* Muenchener Rückversicherungs-Gesellschaft, Munich Reinsurance Company (Munich Re), Munich, Germany, 40 pp.

Munich Re, 2013: *Topics Geo: Natural Catastrophes 2012: Analyses, Assessments, Positions.* Muenchener Rückversicherungs-Gesellschaft, Munich Reinsurance Company (Munich Re), Munich, Germany, 60 pp.

Narita, D., R.S.J. Tol, and D. Anthoff, 2009: Damage costs of climate change through intensification of tropical cyclone activities: an application of FUND. *Climate Research*, **39(2)**, 87-97.

Narita, D., R.S.J. Tol, and D. Anthoff, 2010: Economic costs of extratropical storms under climate change: an application of FUND. *Journal of Environmental Planning and Management*, **53(3)**, 371-384.

Narita, D., K. Rehdanz, and R.S.J. Tol, 2012: Economic costs of ocean acidification: a look into the impacts on global shellfish production. *Climatic Change*, **113(3-4)**, 1049-1063.

Nassopoulos, H., P. Dumas, and S. Hallegatte, 2012: Adaptation to an uncertain climate change: cost benefit analysis and robust decision making for dam dimensioning. *Climatic Change*, **114(3-4)**, 497-508.

National Research Council, 2008: *Potential Impacts of Climate Change on U.S. Transportation*. Transportation Research Board Special Report 290. Committee on Climate Change and U.S. Transportation, Transportation Research Board (TRB) and Division on Earth and Life Studies, National Research Council of the National Academies, TRB, Washington, DC, USA, 280 pp.

Nelson, G., M. Rosegrant, J. Koo, R. Robertson, T. Sulser, R. Zhu, C. Ringler, S. Msangi, A. Palazzo, M. Batka, M. Magalhaes, R. Valmonte-Santos, M. Ewing, and D. Lee, 2009: *Climate Change Impact on Agriculture and Costs of Adaptation.* IFPRI Food Policy Report, International Food Policy Research Institute (IFPRI), Washington, DC, USA, 30 pp.

Nemry, F. and H. Demirel, 2012: *Impacts of Climate Change on Transport: A Focus on Road and Rail Transport Infrastructures*. JRC Scientific and Policy Reports, European Commission, Joint Research Centre, and Institute for Prospective Technological Studies, Publications Office of the European Union, Luxembourg, Luxembourg, 89 pp.

NETL, 2007: *Potential Impacts of Climate Change on the Energy Sector.* DOE/NETL-403/101807, U.S. Government, National Energy Technology Laboratory (NETL), Pittsburgh, PA, USA, 51 pp.

Neumann, J., J. Price, P. Chinowsky, L. Wright, L. Ludwig, R. Streeter, R. Jones, J. Smith, B. Perkins, L. Jantarasami, and J. Martinich, 2013: Climate change risks to United States infrastructure: impacts on coastal development, roads, bridges, and urban drainage. *Climatic Change*, doi:10.1007/s10584-013-1037-4.

Niesing, B., 2004: WIND provides storm warnings. *Fraunhofer Magazine*, **1**, 20-21.

Nordhaus, W. D., 2010: The economics of hurricanes and implications of global warming. *Climate Change Economics*, **1(1)**, 1-20, DOI: 10.1142/S2010007810000054.

Nordhaus, W.D., 2011: The economics of tail events with an application to climate change. *Review of Environmental Economics and Policy*, **5(2)**, 240-257.

Norton, B., 2006: Anatomy of a solar collector: developments in materials, components and efficiency improvements in solar thermal collector systems. *Refocus*, **7(3)**, 32-35.

Noy, I., 2009: The macroeconomic consequences of disasters. *Journal of Development Economics*, **88(2)**, 221-231.

Ntelekos, A.A., M. Oppenheimer, J.A. Smith, and A.J. Miller, 2010: Urbanization, climate change and flood policy in the United States. *Climatic Change*, **103(3)**, 597-616.

Nursey-Bray, M. and T. Miller, 2012: Ports and climate change: building skills in climate change adaptation, Australia. In: *Climate Change and the Sustainable Use of Water Resources* [Filho, W.L. (ed.)]. Springer-Verlag, Berlin and Heidelberg, Germany, pp. 273-282.

Nyaupane, G.P. and N. Chhetri, 2009: Vulnerability to climate change of nature-based tourism in the Nepalese Himalayas. *Tourism Geographies*, **11(1)**, 95-119.

Oliver Wyman, 2007: *Climate Change: Risks and Opportunities for Global Financial Services.* Oliver Wyman, Ltd., New York, NY, USA, 58 pp.

Olonscheck, M., A. Holsten, and J.P. Kropp, 2011: Heating and cooling energy demand and related emissions of the German residential building stock under climate change. *Energy Policy*, **39(9)**, 4795-4806.

Ott, H.E. and C. Richter, 2008: *Anpassung an den Klimawandel – Risiken und Chancen für deutsche Unternehmen*. Wuppertal Papers No. 171, Brief analysis for the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Project: Economic Opportunities Of International Climate Policy (FKZ 90511504), Wuppertal Institit für Klima, Umwelt, Energie GmbH, Wuppertal, Germany, 26 pp.

Ou-Yang, C., H. Kunreuther, and E. Michel-Kerjan, 2013: An economic analysis of climate adaptations to hurricane risk in St. Lucia. *The Geneva Papers*, **38**, 521-546.

Pandey, K., 2010: *Costs of Adapting to Climate Change for Human Health in Developing Countries.* World Bank Development and Climate Change Discussion Paper No.11, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 19 pp.

Pang, S.F.H., B. McKercher, and B. Prideaux, 2013: Climate change and tourism: an overview. *Asia Pacific Journal of Tourism Research*, **18(1-2)**, 4-20.

Parkpoom, S., G.P. Harrison, and J.W. Bialek, 2005: Climate and weather uncertainty in the electricity industry. *International Energy Journal*, **6(1)**, 455-464.

Patt, A., P. Suarez, and U. Hess, 2010: How do small-holder farmers understand insurance, and how much do they want it? Evidence from Africa. *Global Environmental Change*, **20**, 153-161.

Patt, A., Pfenninger S., and J. Lilliestam, 2013: Vulnerability of solar energy infrastructure and output to climate change. *Climatic Change*, **121(1)**, 93-102.

Patton, L., 2011: Why insurers *should* focus on climate risk issues. In: *Risk Management, (SC5), June 2011*. The Geneva Association, The International Association for the Study of Insurance Economics, Geneva, Switzerland, pp. 5-15, www.genevaassociation.org/media/185056/ga2011-rmsc5.pdf.

Paudel, Y., 2012: A comparative study of public – private catastrophe insurance systems: lessons from current practices. *The Geneva Papers*, **37(2)**, 257-285, doi:10.1057/gpp.2012.16.

Pearce, T.D., J.D. Ford, J. Prno, F. Duerden, J. Pittman, M. Beaumier, L. Berrang-Ford, and B. Smit, 2011: Climate change and mining in Canada. *Mitigation and Adaptation Strategies for Global Change*, **16(3)**, 347-368.

Pechan, A. and K. Eisenack, 2013: *The Impact of Heat Waves on Electricity Spot Markets.* Oldenburg Economic Discussion Paper V-357-13, Oldenburg University, Oldenburg, Germany, 31 pp.

Peduzzi, P., B. Chatenoux, H. Dao, A. De Bono, C. Herold, J. Kossin, F. Mouton, and O. Nordbeck, 2012: Global trends in tropical cyclone risk. *Nature Climate Change*, **2**, 289-294, doi:10.1038/NCLIMATE1410.

Pejovic, T., V. Williams, R. Noland, and R. Toumi, 2009: Factors affecting the frequency and severity of airport weather delays and the implications of climate change for future delays. *Journal of the Transportation Research Board*, **2139**, 97-106.

Perch-Nielsen, S.L., 2010: The vulnerability of beach tourism to climate change – an index approach. *Climatic Change*, **100(3)**, 579-606.

Perch-Nielsen, S.L., B. Amelung, and R. Knutti, 2009: Future climate resources for tourism in Europe based on the daily Tourism Climatic Index. *Climatic Change*, **103(3-4)**, 363-381.

Perez-Garcia, J., L.A. Joyce, A.D. Mcguire, and X. Xiao, 2002: Impacts of climate change on the global forest sector. *Climatic Change*, **54(4)**, 439-461.

Phelan, L., R. Taplin, A. Henderson-Sellers, and G. Albrecht, 2011: Ecological viability or liability? Insurance system responses to climate risk. *Environmental Policy and Governance*, **21**, 112-130.

Pickering, C.M. and R.C. Buckley, 2010: Climate response by the ski industry: the shortcomings of snowmaking for Australian resorts. *Ambio*, **39(5-6)**, 430-438.

Pickering, C.M., J.G. Castley, and M. Burtt, 2010: Skiing less often in a warmer world: attitudes of tourists to climate change in an Australian ski resort. *Geographical Research*, **48(2)**, 137-147.

Pielke, R.A.J. and M.W. Downton, 2000: Precipitation and damaging floods: trends in the United States, 1932-97. *Journal of Climate*, **13(20)**, 3625-3637.

Pielke, R.A.J. and C.W. Landsea, 1999: La Nina, El Nino, and Atlantic hurricane damages in the United States. *Bulletin of the American Meteorological Society*, **80**, 2027-2033.

Pinto, J.G., E.L. Fröhlich, G.C. Leckebusch, and U. Ulbrich, 2007: Changing European storm loss potentials under modified climate conditions according to ensemble simulations of the ECHAM5/MPI-OM1 GCM. *Natural Hazards and Earth System Sciences*, **7**, 165-175.

Pinto, J.G., C.P. Neuhaus, G.C. Leckebusch, M. Reyers, and M. Kerschgens, 2009: Estimation of wind storm impacts over Western Germany under future climate conditions using a statistical-dynamical downscaling approach. *Tellus A*, **62**, 188-201.

Pinto, J.G., M.K. Karremann, K. Born, P.M. Della-Marta, and M. Klawa, 2012: Loss potentials associated with European windstorms under future climate conditions. *Climate Research*, **54(1)**, 1-20, doi:10.3354/cr01111.

Pons-Pons, M., P.A. Johnson, M. Rosas-Casals, B. Sureda, and E. Jover, 2012: Modeling climate change effects on winter ski tourism in Andorra. *Climate Research*, **54(3)**, 197-207.

Potocka, I. and A. Zajadacz, 2009: Weather and climate as elements of tourism space controlling the demand for and forms of tourist activity. *Quaestiones Geographicae*, **(28 A1)**, 53-64.

Pouta, E., M. Neuvonen, and T. Sievänen, 2009: Participation in cross-country skiing in Finland under climate change: application of multiple hierarchy stratification perspective. *Journal of Leisure Research*, **41(1)**, 91-108.

Prabhakar, S.V.R.K., G.S. Rao, K. Fukuda, and S. Hayashi, 2013: Promoting risk insurance in the Asia-Pacific region lessons from the ground for the future climate regime under UNFCCC. In: *Climate Change Adaption in Practice: From Strategy Development to Implementation* [Schmidt-Thome, T. and J. Klein (eds.)]. John Wiley & Sons, Ltd., Hoboken, NJ, USA, pp. 303-323.

Prideaux, B. and K.E. Mcnamara, 2012: Turning a global crisis into a tourism opportunity: the perspective from Tuvalu. *International Journal of Tourism Research*, **15(6)**, 583-594.

Pryor, S.C. and R.J. Barthelmie, 2010: Climate change impacts on wind energy: a review. *Renewable and Sustainable Energy Reviews*, **14(1)**, 430-437.

Pryor, S.C. and R.J. Barthelmie, 2011: Assessing climate change impacts on the near-term stability of the wind energy resource over the USA. *Proceedings of the National Academy of Sciences of the United States of America*, **108**, 8167-8171.

Pryor, S.C. and R.J. Barthelmie, 2013: Assessing the vulnerability of wind energy to climate change and extreme events. *Climatic Change*, **121(1)**, 79-91.

Pryor, S.C. and J.T. Schoof, 2010: Importance of the SRES in projections of climate change impacts on near-surface wind regimes. *Meteorologische Zeitschrift*, **19(3)**, 267-274.

Pryor, S.C., J.T. Schoof, and R.J. Barthelmie, 2006: Winds of change? Projections of near-surface winds under climate change scenarios. *Geophysical Research Letters*, **33(11)**, L11702, doi:10.1029/2006GL026000.

Pryor, S.C., R.J. Barthelmie, N.E. Clausen, M. Drews, N. MacKellar, and E. Kjellström, 2011: Analyses of possible changes in intense and extreme wind speeds over northern Europe under climate change scenarios. *Climate Dynamics*, **38**, 189-208.

Qin, D., C. Yiyu, and L. Xueyong, 2005: *Evolution of Climate and Environment in China* (in Chinese). *Science Press*, **1**, 562 pp.

Qiu, L. and W.A. Nixon, 2008: Effects of adverse weather on traffic crashes: systematic review and meta-analysis. *Journal of the Transportation Research Board*, **2055(1)**, 139-146.

Quinto, C., 2011: *Insurance Systems in Times of Climate Change: Insurance of Buildings against Natural Hazards.* Springer, Berlin, Germany, 180 pp.

Qureshi, Z. and D. Reinhard (eds.), 2011: *Making Insurance Work for the Poor*. Proceedings of the 6th International Microinsurance Conference 2010, November 9-11, 2010, Manila, Philippines, Munich Re Foundation in cooperation with the Microinsurance Network, Munich Re Foundation, Munich, Germany, 89 pp.

Raddatz, C., 2009: *The Wrath of God – Macroeconomic Costs of Natural Disasters.* Policy Research Working Paper 5039, The Word Bank Development Research Group, Macroeconomics and Growth Team, The World Bank, Washington, DC, USA, 35 pp.

Raible, C.C., S. Kleppek, M. Wüest, D.N. Bresch, A. Kitoh, H. Murakami, and T.F. Stocker, 2012: Atlantic hurricanes and associated insurance loss potentials in future climate scenarios: limitations of high-resolution AGCM simulations. *Tellus A*, **64**, 15672, doi:10.3402/tellusa.v64i0.15672.

Ramakrishnan, S.K., 2011: Adaptation cost of diarrhea and malaria in 2030 for India. *Indian Journal of Occupational and Environmental Medicine*, **15(2)**, 64-67.

Ranger, N. and F. Niehoerster, 2012: Deep uncertainty in long-term hurricane risk: scenario generation and implications for future climate experiments. *Global Environmental Change*, **22(3)**, 703-712.

Raschky, P.A., R. Schwarze, M. Schwindt, and F. Zahn, 2013: Uncertainty of governmental relief and the crowding out of flood insurance. *Environmental and Resource Economics*, **54**, 179-200.

Ravishankar, N., P. Gubbins, R.J. Cooley, K. Leach-Kemon, C.M. Michaud, T.J. Dean, and J.M. Christopher, 2009: Financing of global health: tracking development assistance for health from 1990 to 2007. *Lancet*, **373(9681)**, 2113-2124.

Raymond, C.M. and G. Brown, 2011: Assessing spatial associations between perceptions of landscape value and climate change risk for use in climate change planning. *Climatic Change*, **104(3-4)**, 653-678.

Reed, D.A., 2008: Electric utility distribution analysis for extreme winds. *Journal of Wind Engineering and Industrial Aerodynamics*, **96(1)**, 123-140.

Reilly, J.M., N. Hohmann, and S. Kane, 1994: Climate change and agricultural trade: who benefits, who loses? *Global Environmental Change*, **4(1)**, 24-36.

Reilly, J.M., S. Paltsev, B. Felzer, X. Wang, D.W. Kicklighter, J.M. Melillo, R.G. Prinn, M. Sarofim, A.P. Sokolov, and C. Wang, 2007: Global economic effects of changes in crops, pasture, and forests due to changing climate, carbon dioxide, and ozone. *Energy Policy*, **35**, 5370-5383.

Reinhold, T., B. O'Connor, and C. Iskowitz, 2012: Reducing vulnerabilities through science. In: *Severe Weather in North America. Perils, Risks, Insurance* [Kron, W. and F. Wöst (eds.)]. Munich Re, Munich, Germany, pp. 197-225.

Guoyu, G.Y., 1996: Global climate changes and the tourism of China. *Journal of Chinese Geography*, **6(2)**, 97-102.

Richardson, R.B. and J.B. Loomis, 2005: Climate change and recreation benefits in an alpine national park. *Journal of Leisure Research*, **37(3)**, 307-320.

Richter, C., S. Teske, and R. Short, 2009: *Concentrating Solar Power: Global Outlook 2009 – Why Renewable Energy is Hot.* Greenpeace International, Amsterdam, Netherlands, ESTALA, Brussels, Belgium, and IEA SolarPaces, Tabernas, Spain, 87 pp.

Rising, W.R., J.A. O'Daniel, and C.S. Roberts, 2006: Correlating weather and trauma admissions at a level I trauma center. *Journal of Trauma – Injury, Infection and Critical Care*, **60(5)**, 1096-1110.

Robinson, S., K. Strzepek, and R. Cervigni, 2013: *The Cost of Adapting to Climate Change in Ethiopia*. Ethiopia Strategy Support Program II Working Paper 53, IFPRI ESSP WP 53, 2013.

Ronneberger, K., M. Berrittella, F. Bosello, and R.S.J. Tol, 2009: KLUM@GTAP: introducing biophysical aspects of land-use decisions into a computable general equilibrium model, a coupling experiment. *Environmental Modeling and Assessment*, **14(2)**, 149-168.

Roson, R. and D. van der Mensbrugghe, 2012: Climate change and economic growth: impacts and interactions. *International Journal of Sustainable Economy*, **4(3)**, 270-285.

Rossello, J., 2011: North Atlantic Oscillation influences on European airline traffic. *Transportation Research Part D: Transport and Environment*, **16(2)**, 183-187.

Rosselló-Nadal, J., A. Riera-Font, and V. Cárdenas, 2010: The impact of weather variability on British outbound flows. *Climatic Change*, 105(1-2), 281-292.

Rübbelke, D.T.G. and S. Vögele, 2010: *Impacts of Climate Change on European Critical Infrastructures: The Case of the Power Sector*. Basque Centre for Climate Change (BC3) Working Paper 2010-08, BC3, Bilbao, Spain, 20 pp.

Rübbelke, D. and S. Vögele, 2013: Short-term distributional consequences of climate change impacts on the power sector: who gains and who loses? *Climatic Change*, **116(2)**, 191-206.

Rummukainen, M., 2013: Climate change: changing means and changing extremes. *Climatic Change*, **121(1)**, 3-13.

Rutty, M. and D. Scott, 2010: Will the Mediterranean become "too hot" for tourism? A reassessment. *Tourism and Hospitality, Planning and Development*, **7(3)**, 267-281.

Ryley, T. and L. Chapman (eds.), 2012: *Transport and Sustainability, Vol. 2: Transport and Climate Change*. Emerald Group Publishing, Ltd., Bingley, UK, 396 pp.

Saarinen, J. and K. Tervo, 2006: Perceptions and adaptation strategies of the tourism industry to climate change: the case of Finnish nature-based tourism entrepreneurs. *International Journal of Innovation and Sustainable Development*, **1(3)**, 214-228.

Saarinen, J., W.L. Hambira, J. Atlhopheng, and H. Manwa, 2012: Tourism industry reaction to climate change in Kgalagadi South District, Botswana. *Development Southern Africa*, **29(2)**, 273-285.

Sabbioni, C., M. Cassar, P. Brimblecombe, and R.A. Lefevre, 2009: Vulnerability of cultural heritage to climate change. *Pollution Atmospherique*, **(202)**, 157-169.

Sailor, D.J., M. Smith, and M. Hart, 2008: Climate change implications for wind power resources in the Northwest United States. *Renewable Energy*, **33(11)**, 2393-2406.

Sander, J., J.F. Eichner, E. Faust, and M. Steuer, 2013: Rising variability in thunderstorm-related U.S. losses as a reflection of changes in large-scale thunderstorm forcing. *Weather, Climate, and Society*, **5**, 317-331, doi:10.1175/WCAS-D-12-00023.1.

Schaefli, B., D. Balin Talamba, and A. Musy, 2007: Quantifying hydrological modeling errors through a mixture of normal distributions. *Journal of Hydrology*, **332**, 303-315.

Schmidt, P., R. Steiger, and A. Matzarakis, 2012: Artificial snowmaking possibilities and climate change based on regional climate modeling in the Southern Black Forest. *Meteorologische Zeitschrift*, **21(2)**, 167-172.

Schreider, S.Y., D.I. Smith, and A.J. Jakeman, 2000: Climate change impacts on urban flooding. *Climatic Change*, **47(1-2)**, 91-115.

Schwarze, R. and G.G. Wagner, 2007: The political economy of natural disaster insurance: lessons from the failure of a proposed compulsory insurance scheme in Germany. *European Environment*, **17(6)**, 403-415.

Schwarze, R., H. Schwindt, H. Weck-Hannemann, P. Raschky, F. Zahn, and G.G. Wagner, 2011: Natural hazard insurance in Europe: tailored responses to climate change are needed. *Environmental Policy and Governance*, **21**, 14-30.

Schwierz, C., P. Köllner-Heck, E. Zenklusen-Mutter, D.N. Bresch, P.-L. Vidale, M. Wild, and C. Schär, 2010: Modelling European winter wind storm losses in current and future climate. *Climatic Change*, **101(3-4)**, 485-514.

Scott, D. and B. Jones, 2006: The impact of climate change on golf participation in the Greater Toronto Area (GTA): a case study. *Journal of Leisure Research*, **38(3)**, 363-380.

Scott, D. and B. Jones, 2007: A regional comparison of the implications of climate change for the golf industry in Canada. *Canadian Geographer*, **51(2)**, 219-232.

Scott, D. and G. McBoyle, 2007: Climate change adaptation in the ski industry. *Mitigation and Adaptation Strategies for Global Change*, **12(8)**, 1411-1431.

Scott, D., G. McBoyle, and B. Mills, 2003: Climate change and the skiing industry in southern Ontario (Canada): exploring the importance of snowmaking as a technical adaptation. *Climate Research*, **23(2)**, 171-181.

Scott, D., G. McBoyle, A. Minogue, and B. Mills, 2006: Climate change and the sustainability of ski-based tourism in eastern North America: a reassessment. *Journal of Sustainable Tourism*, **14(4)**, 376-398.

Scott, D., B. Jones, and J. Konopek, 2007: Implications of climate and environmental change for nature-based tourism in the Canadian Rocky Mountains: a case study of Waterton Lakes National Park. *Tourism Management*, **28(2)**, 570-579.

Scott, D., G. McBoyle, and A. Minogue, 2007: Climate change and Quebec's ski industry. *Global Environmental Change*, **17(2)**, 181-190.

Scott, D., J. Dawson, and B. Jones, 2008a: Climate change vulnerability of the US Northeast winter recreation- tourism sector. *Mitigation and Adaptation Strategies for Global Change*, **13(5-6)**, 577-596.

Scott, D., S. Gössling, and C.R. De Freitas, 2008b: Preferred climates for tourism: case studies from Canada, New Zealand and Sweden. *Climate Research*, **38(1)**, 61-73.

Scott, D., S. Gössling, and C.M. Hall, 2012a: International tourism and climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **3(3)**, 213-232.

Scott, D., M.C. Simpson, and R. Sim, 2012b: The vulnerability of Caribbean coastal tourism to scenarios of climate change related sea level rise. *Journal of Sustainable Tourism*, **20(6)**, 883-898.

Scott, M., S. Gupta, E. Jáuregui, J. Nwafor, D. Satterthwaite, W. Wanasinghe, and M. Yoshino, 2001: Human settlements, energy and industry. In: *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [McCarthy, J.J., O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 381-416.

Seo, J. and O. Mahul, 2009: *The Impact of Climate Change on Catastrophe Risk Model. Implications for Catastrophe Risk Markets in Developing Countries*. Policy Research Working Paper 4959, A joint product of the World Bank Global Facility for Disaster Reduction and Recovery Unit, Sustainable Development Network Vice Presidency, and the Global Capital Markets Development Department, Financial and Private Sector Development Vice Presidency, The World Bank, Washington, DC, USA, 16 pp.

Seppala, R., A. Buck, and P. Katila (eds.), 2009: *Adaptation of Forests and People to Climate Change – A Global Assessment Report.* IUFRO World Series Vol. 22, International Union of Forest Research Organizations (IUFRO), IUFRO, Helsinki, Finland, 224 pp.

Serquet, G. and M. Rebetez, 2011: Relationship between tourism demand in the Swiss Alps and hot summer air temperatures associated with climate change. *Climatic Change*, **108(1-2)**, 291-300.

Shaw, W.D. and J.B. Loomis, 2008: Frameworks for analyzing the economic effects of climate change on outdoor recreation. *Climate Research*, **36(3)**, 259-269.

Sherement, O. and A. Lucas, 2009: Global loss diversification in the insurance sector. *Insurance: Mathematics and Economics*, **44(3)**, 415-425, doi:10.1016/j.insmatheco.2008.12.001.

Shih, C., S. Nicholls, and D.F. Holecek, 2009: Impact of weather on downhill ski lift ticket sales. *Journal of Travel Research*, **47(3)**, 359-372.

Sieber, J., 2013: Impacts of, and adaptation options to, extreme weather events and climate change concerning thermal power plants. *Climatic Change*, **121(1)**, 55-66.

Skidmore, M. and H. Toya, 2002: Do natural disasters promote long-term growth? *Economic Inquiry*, **40(4)**, 664-687.

Smith, A.B. and R.W. Katz, 2013: US billion-dollar weather and climate disasters: data sources, trends, accuracy and biases. *Natural Hazards*, **67(2)**, 387-410, doi:10.1007/s11069-013-0566-5.

Sohngen, B. and R. Mendelsohn, 1997: A dynamic model of forest carbon storage in the United States during climatic change. *Critical Reviews in Environmental Science and Technology*, **27(SI)**, S309-S321.

Sohngen, B. and R. Mendelsohn, 1998: Valuing the impact of large-scale ecological change in a market: the effect of climate change on U.S. timber. *American Economic Review*, **88(4)**, 686-710.

Sohngen, B., R. Mendelsohn, and R. Sedjo, 2001: A global model of climate change impacts on timber markets. *Journal of Agricultural and Resource Economics*, **26(2)**, 326-343.

Steger, C., S. Kotlarski, T. Jonas, and C. Schär, 2012: Alpine snow cover in a changing climate: a regional climate model perspective. *Climate Dynamics*, **41(3-4)**, 735-754.

Steiger, R., 2010: The impact of climate change on ski season length and snowmaking requirements in Tyrol, Austria. *Climate Research*, **43(3)**, 251-262.

Steiger, R., 2012: Scenarios for skiing tourism in Austria: integrating demographics with an analysis of climate change. *Journal of Sustainable Tourism*, **20(6)**, 867-882.

Steiger, R. and M. Mayer, 2008: Snowmaking and climate change: future options for snow production in Tyrolean ski resorts. *Mountain Research and Development*, **28(3-4)**, 292-298.

Stenek, V., J.C. Amado, and R. Connell, 2010: *Climate Risk and Financial Institutions: Challenges and Opportunities* [Kamins, R., A. Hidalgo, V. Stenek, and R. Connell (eds.)]. International Finance Corporation (IFC), World Bank Group, Washington, DC, USA, 120 pp.

Stewart, E.J., S.E.L. Howell, D. Draper, J. Yackel, and A. Tivy, 2007: Sea ice in Canada's Arctic: implications for cruise tourism. *Arctic*, **60(4)**, 370-380.

Stewart, W. and D. Willard, 2010: Kivalina v. ExxonMobil dismissed by Federal trial court. In: *Liability for Climate Change? Experts' Views on a Potential Emerging Risk.* Munich Re, Munich, Germany, pp. 11-13.

Strulik, H., 2008: Geography, health, and the pace of demo-economic development. *Journal of Development Economics*, **86(1)**, 61-75.

Strzepek, K., Y. Gary, N. James, and B. Brent, 2010: Characterizing changes in drought risk for the United States from climate change. *Environmental Research Letters*, **5**, 044012, doi:10.1088/1748-9326/5/4/044012.

Strzepek, K., B. Boehlert, A. McCluskey, W. Farmer, J. Neumann, and M. Fuchs, 2011: *Assessment of the Impacts of Climate Change on Multi-Sector Investment Opportunities in the Zambezi River Basin.* IEC Report to The World Bank, World Bank, Washington, DC, USA, pp.

Strzepek, K., J. Smith, J. Martinich, J. Neumann, B. Boehlert, M. Hejazi, J. Henderson, C. Wobus, K. Calvin, D. Johnson, J. R., E. Monier, J. Strzepek, and J. Yoon, 2013: Climate change impacts on water resources in the United States. *Climatic Change*, (under review).

Subak, S., J.P. Palutikof, M.D. Agnew, S.J. Watson, C.G. Bentham, M.G.R. Cannell, M. Hulme, S. McNally, J.E. Thornes, D. Waughray, and J.C. Woods, 2000: The impact of the anomalous weather of 1995 on the U.K. economy. *Climatic Change*, **44(1-2)**, 1-26.

Supreme Court of Virginia, USA, 2012: Declaratory judgment following rehearing. In: *The AES Corporation v. Steadfast Insurance Company, Record No.100764: Opinion by Justice S. Bernard Goodwyn, April 20, 2012*. Supreme Court of Virginia, USA, Richmond, VA, USA, www.courts.state.va.us/opinions/opnscwp/1100764r.pdf.

Sweeney, M., A. Gasca, M. Garcia-Lopez, and A.C. Palmer, 2005: Pipelines and landslides in rugged terrain: a database, historic risks and pipeline vulnerability. In: *International Conference on Terrain and Geohazard Challenges Facing Onshore Oil and Gas Pipelines: Evaluation, Routing, Design, Construction, Operation* [Sweeney, M. (ed.)]. Institution of Civil Engineers in coordination with BP Exploration, Thomas Telford, Ltd., London, UK, pp. 641-659.

Swiss Re, 2013a: *SIGMA No. 1/2013: Partnering for Food Security in Emerging Markets.* Economic Research & Consulting, Swiss Reinsurance Company, Ltd. (Swiss Re), Zürich, Switzerland, 40 pp.

Swiss Re, 2013b: *SIGMA No. 3/2013: World Insurance in 2012: Progressing on the Long and Winding Road to Recovery*. Economic Research & Consulting, Swiss Reinsurance Company, Ltd. (Swiss Re), Zürich, Switzerland, 42 pp.

Swiss Re, 2013c: *SIGMA No. 2/2012: Natural Catastrophes and Man-Made Disasters in 2012: A Year of Extreme Weather Events in the US*. Economic Research & Consulting, Swiss Reinsurance Company, Ltd. (Swiss Re), Zürich, Switzerland, 44 pp.

Tamiotti, L., R. Teh, V. Kalucoglu, A. Olhoff, B. Simmons, and H. Abaza, 2009: *Trade and Climate Change.* World Trade Organization (WTO) and the United Nations Environment Programme (UNEP), WTO, Geneva, Switzerland, 166 pp.

Tang, K.K., D. Petrie, and D.S.P. Rao, 2009: The income-climate trap of health development: a comparative analysis of African and Non-African countries. *Social Science and Medicine*, **69(7)**, 1099-1106.

Taylor, R.J. and H.M. Tollin, 2009: Insurance market for global warming heats up: old products and new policies respond to climate change risks. *Environmental Claims Journal*, **21(3)**, 247-261.

Taylor, T. and R.A. Ortiz, 2009: Impacts of climate change on domestic tourism in the UK: a panel data estimation. *Tourism Economics*, **15(4)**, 803-812.

Tervo, K., 2008: The operational and regional vulnerability of winter tourism to climate variability and change: the case of the Finnish nature-based tourism entrepreneurs. *Scandinavian Journal of Hospitality and Tourism*, **8(4)**, 317-332.

Thieken, A.H., T. Petrow, H. Kreiblich, and B. Merz, 2006: Insurability and mitigation of flood losses in private households in Germany. *Risk Analysis*, **26**, 383-395.

Tol, R.S.J., 2008: Why worry about climate change? A research agenda. *Environmental Values*, **17(4)**, 437-470.

Tol, R.S.J., 2011: The social cost of carbon. *Annual Review of Resource Economics*, **3**, 419-443.

Tol, R.S.J., 2013: Targets for global climate policy: an overview. *Journal of Economic Dynamics and Control*, **37(5)**, 911-928.

Towler, E., B. Raucher, B. Rajagopalan, A. Rodriguez, D. Yates, and R. Summers, 2011: Incorporating climate uncertainty in a cost assessment for a new municipal source water. *Journal of Water Resources Planning and Management*, **138(5)**, 396-402.

Trærup, S.L.M., 2012: Informal networks and resilience to climate change impacts: a collective approach to index insurance. *Global Environmental Change*, **22**, 255-267.

Trærup, S.L.M., R.A. Ortiz, and A. Markandya, 2011: The costs of climate change: a study of cholera in Tanzania. *International Journal of Environmental Research and Public Health*, **8(12)**, 4386-4405.

Travers, J. and V.G. Payne, 1998: The impact of climate change on traditional seasonal ranges for High Street women's wear in England. *Journal of Fashion Marketing and Management*, **2(4)**, 370-382.

Troccoli, A. (ed.), 2010: *Management of Weather and Climate Risk in the Energy Industry*. Springer, Dordrecht, Netherlands, 330 pp.

Tsai, H.-T., C.-J. Tseng, S.-Y. Tzeng, T.-J. Wu, and J.-d. Day, 2012: The impacts of natural hazards on Taiwan's tourism industry. *Natural Hazards*, **62(1)**, 83-91.

Turton, S., T. Dickson, W. Hadwen, B. Jorgensen, T. Pham, D. Simmons, P. Tremblay, and R. Wilson, 2010: Developing an approach for tourism climate change assessment: evidence from four contrasting Australian case studies. *Journal of Sustainable Tourism*, **18(3)**, 429-447.

UNCTAD, 2009: *Multi-Year Expert Meeting on Transport and Trade Facilitation: Maritime Transport and the Climate Change Challenge, 16 – 18 February 2009, Geneva, Summary of Proceedings.* UNCTAD/DTL/TLB/2009/1 United Nations Conference on Trade and Development (UNCTAD), Geneva, Switzerland, 47 pp.

UNDP, 2011: The economic impacts of climate change on energy demand for space heating and cooling. In: *Assessing the Economic Impact of Climate Change – National Case Studies*. United Nations Development Program (UNDP), New York, NY, USA, pp. 37-56.

UNECE and UNCTAD, 2010: *Note by the United Nations Economic Commission for Europe (UNECE) and United Nations Conference on Trade and Development (UNCTAD) Secretariats.* Proceedings of Joint Workshop on Climate Change Impacts on International Transport Networks, 7 – 8 September 2010, Geneva, ECE/TRANS/WP.5/2010/3, UNECE and UNCTAD, Geneva, Switzerland, 14 pp.

UNFCCC, 2007: *Investment and Financial Flows to Address Climate Change.* United Nations Framework Convention on Climate Change (UNFCCC), Bonn, Germany, 272 pp.

URS, 2010: *Adapting Energy, Transport, and Water Infrastructure to the Long-Term Impacts of Climate Change, Summary Report.* Reference No. RMP/5456, Report by URS Corporation, Ltd. for the UK Government's cross-departmental Infrastructure and Adaptation Project, URS Corporation, Ltd., London, UK, 16 pp.

Uyarra, M.C., I.M. Côté, J.A. Gill, R.R.T. Tinch, D. Viner, and A.R. Watkinson, 2005: Island-specific preferences of tourists for environmental features: implications of climate change for tourism-dependent states. *Environmental Conservation*, **32(1)**, 11-19.

van den Berg, M., 2010: Household income strategies and natural disasters: dynamic livelihoods in rural Nicaragua. *Ecological Economics*, **69(3)**, 592-602.

Van den Bergh, R. and M. Faure, 2006: Compulsory insurance of loss to property caused by natural disasters: competition or solidarity? *World Competition*, **29(1)**, 25-54.

Van der Vliert, E., 2008: *Climate, Affluence, and Culture*. Cambridge University Press, New York, NY, USA, 253 pp.

Van Nostrand, J.M. and J.G. Nevius, 2011: Parametric insurance: using objective measures to address the impacts of natural disasters and climate change. *Environmental Claims Journal*, **23(3-4)**, 227-237.

van Rensburg, J.J.J. and J.N. Blignaut, 2002: The economic impact of an increasing health risk due to global warming. In: *Forum for Economics and Environment – First Conference Proceedings.* Economics for Environment Forum (Econ4Env), Cape Town, South Africa, pp. 117-141, citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.199.630&rep=rep1&type=pdf.

Van Vliet, M.T.H., J.R. Yearsley, F. Ludwig, S. Vögele, D.P. Lettenmaier, and P. Kabat, 2012: Vulnerability of US and European electricity supply to climate change. *Nature Climate Change*, **2(9)**, 676-681.

Vergara, W., A. Deeb, A. Valencia, R. Bradley, B. Francou, A. Zarzar, A. Grunwaldt, and S. Haeussling, 2007: Economic impacts of rapid glacier retreat in the Andes. *Eos, Transactions American Geophysical Union*, **88(25)**, 261-268.

Vlasova, L.V. and G.S. Rakitina, 2010: Natural risks management in the Gas Transmission System (GTS) of Russia and the contribution of climate services under global climate change. In: *Management of Weather and Climate Risk in the Energy Industry* [Troccoli, A. (ed.)]. Springer, Bilthoven, Netherlands, pp. 315-325.

von Peter, G., S. von Dahlen, and S. Saxena, 2012: *Unmitigated Disasters? New Evidence on the Macroeconomic Cost of Natural Catastrophes*. BIS Working Paper No. 394, Monetary and Economic Department of the Bank for International Settlements, Basel, Switzerland, 38 pp.

Walter, A., K. Keuler, D. Jacob, R. Knoche, A. Block, S. Kotlarski, G. Muller-Westermeier, D. Rechid, and W. Ahrens, 2006: A high resolution reference data set of German wind velocity 1951-2001 and comparison with regional climate model results. *Meteorologische Zeitschrift*, **15**, 585-596.

Wang, S., Y. He, and X. Song, 2010: Impacts of climate warming on Alpine glacier tourism and adaptive measures: a case study of Baishui Glacier No. 1 in Yulong Snow Mountain, Southwestern China. *Journal of Earth Science*, **21(2)**, 166-178.

Ward, A.M., 2013: The effect of weather on grid systems and the reliability of electricity supply. *Climatic Change*, **121(1)**, 103-113.

Ward, R.E.T., C. Herweijer, N. Patmore, and R. Muir-Wood, 2008: The role of insurers in promoting adaptation to the impacts of climate change. *The Geneva Papers*, **33**, 133-139.

Ward, P.J., K.M. Strzepek, W.P. Pauw, L.M. Brander, G.A. Hughes, and J.C.J.H. Aerts, 2010: Partial costs of global climate change adaptation for the supply of raw industrial and municipal water: a methodology and application. *Environmental Research Letters*, **5(4)**, 044011, doi:10.1088/1748-9326/5/4/044011.

Warner, K. and A. Spiegel, 2009: Climate change and emerging markets: the role of the insurance industry in climate change management. In: *The Geneva Reports – Risk and Insurance Research No. 2. The Insurance Industry and Climate Change – Contribution to the Global Debate*. The Geneva Association, The International Association for the Study of Insurance Economics, Geneva, Switzerland, pp. 83-95.

Warner, K., S. Kreft, M. Zissner, P. Höppe, C. Bals, T. Loster, J. Linnerooth-Bayer, S. Tschudi, E. Gurenko, A. Haas, S. Young, P. Kovacs, A. Dlugolecki, and A. Oxley, 2012: *Insurance Solutions in the Context of Climate Change-Related Loss and Damage: Needs, Gaps, and Roles of the Convention in addressing Loss and Damage.* UNU-EHS Publication Series Policy Brief No. 6, Munich Climate Insurance Initiative (MCII) hosted by United Nations University-Institute for Environment and Human Security (UNU-EHS), Bonn, Germany, 47 pp.

Watkiss, P. and A. Hunt, 2012: Projection of economic impacts of climate change in sectors of Europe based on bottom up analysis: human health. *Climatic Change*, **112(1)**, 101-126.

Weitzman, M.L., 2009: On modeling and interpreting the economics of catastrophic climate change. *Review of Economics and Statistics*, **91(1)**, 1-19.

Welker, C. and E. Faust, 2013: Tropical cyclone-related socio-economic losses in the western North Pacific region. *Natural Hazards and Earth System Sciences*, **13**, 115-124, doi:10.5194/nhess-13-115-2013.

Whalley, J. and Y. Yuan, 2009: Global financial structure and climate change. *Journal of Financial Transformation*, **25**, 161-168.

Whitehead, J.C., B. Poulter, C.F. Dumas, and O. Bin, 2009: Measuring the economic effects of sea level rise on shore fishing. *Mitigation and Adaptation Strategies for Global Change*, **14(8)**, 777-792.

WHO, 2004: *Evaluation of the Costs and Benefits of Water and Sanitation Improvements at the Global Level.* WHO/SDE/WSH/04.04, Water, Sanitation and Health Protection of the Human Environment, World Health Organization (WHO), Geneva, Switzerland, 87 pp.

Wilbanks, T.J., P. Romero Lankao, M. Bao, F. Berkhout, S. Cairncross, J.-P. Ceron, M. Kapshe, R. Muir-Wood, and R. Zapata-Marti, 2007: Industry, settlement and society. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (ed.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 357-390.

Wilcox, R., J. Syroka, F. Kassam, and S. Mapfumo, 2010: *African Risk Capacity (ARC) Briefing Book.* The African Risk Capacity (ARC) Project initiated by the African Union Commission, Department of Rural Economy and Agriculture, and the United Nations World Food Programme (WFP), ARC, Johannesburg, South Africa, 48 pp.

Williams, E., 2013: Economy-wide and sectoral implications of climate change and extreme weather impacts on the energy sector. In: *Climate Change Impacts on the Energy Sector*. Interim Report, International Atomic Energy Agency (IAEA), Vienna, Austria, pp. 18-33.

Williams, E. and F.L. Toth, 2013: Nuclear power: impacts of climate change and extreme weather. In: *Climate Change Impacts on the Energy Sector.* Interim Report, International Atomic Energy Agency (IAEA), Vienna, Austria, pp. 1-17.

Williams, P.D. and M.M. Joshi, 2013: Intensification of winter transatlantic aviation turbulence in response to climate change. *Nature Climate Change*, **3**, 644-648.

Wilson, K.J., J. Falkingham, H. Melling, and R. De Abreu, 2004: Shipping in the Canadian Arctic: other possible climate change scenarios. In: *IGARSS, 2004. Proceedings of the 2004 IEEE International Geoscience and Remote Sensing Symposium: Science for Society, Exploring and Managing a Changing Planet, Anchorage, Alaska, 20 – 24 September 2004*. Institute of Electrical and Electronics Engineers (IEEE), New York, NY, USA, pp. 1853-1856.

Winkler, J., L. Dueñas-Osorio, R. Stein, and D. Subramanian, 2010: Performance assessment of topologically diverse power systems subjected to hurricane events. *Reliability Engineering and System Safety*, **95(4)**, 323-336.

Winters, P., R. Murgai, E. Sadoulet, A. De Janvry, and G. Frisvold, 1998: Economic and welfare impacts of climate change on developing countries. *Environmental and Resource Economics*, **12(1)**, 1-24.

Wirtz, A., P. Löw, T. Mahl, and S. Yildirim, 2013: Hitting the poor – public private partnerships as an option: impact of natural catastrophes in economies at various stages of development. In: *Extreme Natural Hazards, Disaster Risks and Societal Implications* [Ismail-Zadeh, A., J. Fucugauchi, A. Kijko, K. Takeuchi, and I. Zaliapin (eds.)]. Cambridge University Press, Cambridge, UK (in press).

Wobus, C., M. Lawson, R. Jones, J. Smith, and J. Martinich, 2013: Estimating monetary damages from flooding in the United States under a changing climate. *Journal of Flood Risk Management* (in press), doi:10.1111/jfr3.12043.

Wolfsegger, C., S. Gössling, and D. Scott, 2008: Climate change risk appraisal in the Austrian ski industry. *Tourism Review International*, **12(1)**, 13-23.

World Bank, 2006: *Ethiopia: Managing Water Resources to Maximize Sustainable Growth.* Country Water Resources Assistance Strategy, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 91 pp.

World Bank, 2013: *Pacific Catastrophe Risk Insurance Pilot. Regional Financial Protection Against Natural Disasters for Pacific Island States*. Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI), 4 pp. http://siteresources.worldbank.org/EXTDISASTER/Resources/8308420-1361321776050/Pacific-Catastrophe-Risk-Insurance-Pilot_4pager_12Feb13.pdf.

Wright, L., P. Chinowsky, K. Strzepek, R. Jones, R. Streeter, J.B. Smith, J.-M. Mayotte, A. Powell, L. Jantarasami, and W. Perkins, 2012: Estimated effects of climate change on flood vulnerability of U.S. bridges. *Mitigation and Adaptation Strategies for Global Change*, **17(8)**, 939-955.

WTO and UNEP, 2008: *Climate Change and Tourism – Responding to Global Challenges.* World Tourism Organization (WTO) and United Nations Environment Programme (UNEP), WTO, Madrid, Spain, 256 pp.

WTTC, 2011: *Travel & Tourism 2011.* World Travel and Tourism Council (WTTC), London, UK, 40 pp.

Yates, D.N. and K.M. Strzepek, 1998: An assessment of integrated climate change impacts on the agricultural economy of Egypt. *Climatic Change*, **38(3)**, 261-287.

Yazdi, S.K. and A. Fashandi, 2010: The economic effects of climate change on fisheries and aquaculture. In: *2010 International Conference on Environmental Engineering and Applications (ICEEA 2010)*. Proceedings of a meeting held 10 – 12 September 2010, Singapore, Institute of Electrical and Electronics Engineers (IEEE), New York, NY, USA, pp. 335-340.

Yohe, G.W., 2008: A research agenda to improve economic estimates of the benefits of climate change policies. *Integrated Assessment*, **8(1)**, 1-17.

Yu, G., Z. Schwartz, and J.E. Walsh, 2009a: A weather-resolving index for assessing the impact of climate change on tourism related climate resources. *Climatic Change*, **95(3-4)**, 551-573.

Yu, G., S. Zvi, and J.E. Walsh, 2009b: Effects of climate change on the seasonality of weather for tourism in Alaska. *Arctic*, **62(4)**, 443-457.

Zachariadis, T., 2010: Forecast of electricity consumption in Cyprus up to the year 2030: The potential impact of climate change. *Energy Policy*, **38(2)**, 744-750.

Zahran, S., S. Weiler, S.D. Brody, M.K. Lindell, and W.E. Highfield, 2009: Modeling national flood insurance policy holding at the county scale in Florida, 1999-2005. *Ecological Economics*, **68(10)**, 2627-2636.

Zaninović, K. and A. Matzarakis, 2009: The bioclimatological leaflet as a means conveying climatological information to tourists and the tourism industry. *International Journal of Biometeorology*, **53(4)**, 369-374.

Zhu, J., 2011: Evaluation of an insurance scheme based on the weather index – a case study of Anhui Province. *The Chinese Economy*, **44(6)**, 56-72.

Zimmerman, F.J. and M.R. Carter, 2003: Asset smoothing, consumption smoothing and the reproduction of inequality under risk and subsistence constraints. *Journal of Development Economics*, **71(2)**, 233-260.

11 Human Health: Impacts, Adaptation, and Co-Benefits

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This chapter should be cited as:
Smith, K.R., A. Woodward, D. Campbell-Lendrum, D.D. Chadee, Y. Honda, Q. Liu, J.M. Olwoch, B. Revich, and R. Sauerborn, 2014: Human health: impacts, adaptation, and co-benefits. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 709-754.

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Executive Summary

The health of human populations is sensitive to shifts in weather patterns and other aspects of climate change (*very high confidence*). These effects occur directly, due to changes in temperature and precipitation and occurrence of heat waves, floods, droughts, and fires. Indirectly, health may be damaged by ecological disruptions brought on by climate change (crop failures, shifting patterns of disease vectors), or social responses to climate change (such as displacement of populations following prolonged drought). Variability in temperatures is a risk factor in its own right, over and above the influence of average temperatures on heat-related deaths. {11.4} Biological and social adaptation is more difficult in a highly variable climate than one that is more stable. {11.7}

Until mid-century climate change will act mainly by exacerbating health problems that already exist (*very high confidence*). New conditions may emerge under climate change (*low confidence*), and existing diseases (e.g., food-borne infections) may extend their range into areas that are presently unaffected (*high confidence*). But the largest risks will apply in populations that are currently most affected by climate-related diseases. Thus, for example, it is expected that health losses due to climate change-induced undernutrition will occur mainly in areas that are already food-insecure. {11.3}

In recent decades, climate change has contributed to levels of ill health (*likely*) though the present worldwide burden of ill health from climate change is relatively small compared with other stressors on health and is not well quantified. Rising temperatures have increased the risk of heat-related death and illness (*likely*). {11.4} Local changes in temperature and rainfall have altered distribution of some water-borne illnesses and disease vectors, and reduced food production for some vulnerable populations (*medium confidence*). {11.5-6}

If climate change continues as projected across the Representative Concentration Pathway (RCP) scenarios, the major changes in ill health compared to no climate change will occur through:

- Greater risk of injury, disease, and death due to more intense heat waves and fires (*very high confidence*) {11.4}
- Increased risk of undernutrition resulting from diminished food production in poor regions (*high confidence*) {11.6}
- Consequences for health of lost work capacity and reduced labor productivity in vulnerable populations (*high confidence*) {11.6}
- Increased risks of food- and water-borne diseases (*very high confidence*) and vector-borne diseases (*medium confidence*) {11.5}
- Modest reductions in cold-related mortality and morbidity in some areas due to fewer cold extremes (*low confidence*), geographical shifts in food production, and reduced capacity of disease-carrying vectors due to exceedance of thermal thresholds (*medium confidence*). These positive effects will be increasingly outweighed, worldwide, by the magnitude and severity of the negative effects of climate change (*high confidence*). {11.4-6}

Impacts on health will be reduced, but not eliminated, in populations that benefit from rapid social and economic development (*high confidence*), particularly among the poorest and least healthy groups (*very high confidence*). {11.4, 11.6-7} Climate change is an impediment to continued health improvements in many parts of the world. If economic growth does not benefit the poor, the health effects of climate change will be exacerbated.

In addition to their implications for climate change, essentially all the important climate-altering pollutants (CAPs) other than carbon dioxide (CO_2) have near-term health implications (*very high confidence*). In 2010, more than 7% of the global burden of disease was due to inhalation of these air pollutants (*high confidence*). {Box 11-4}

Some parts of the world already exceed the international standard for safe work activity during the hottest months of the year. The capacity of the human body to thermoregulate may be exceeded on a regular basis, particularly during manual labor, in parts of the world during this century. In the highest Representative Concentration Pathway, RCP8.5, by 2100 some of the world's land area will be experiencing 4°C to 7°C higher temperatures due to anthropogenic climate change (WGI AR5 Figure SPM.7). If this occurs, the combination of high temperatures and high humidity will compromise normal human activities, including growing food or working outdoors in some areas for parts of the year (*high confidence*). {11.8}

The most effective measures to reduce vulnerability in the near term are programs that implement and improve basic public health measures such as provision of clean water and sanitation, secure essential health care including vaccination and child health services, increase capacity for disaster preparedness and response, and alleviate poverty (*very high confidence*). {11.7} In addition, there has been progress since AR4 in targeted and climate-specific measures to protect health, including enhanced surveillance and early warning systems. {11.7}

There are opportunities to achieve co-benefits from actions that reduce emissions of warming CAPs and at the same time improve health. Among others, these include:

- Reducing local emissions of health-damaging and climate-altering air pollutants from energy systems, through improved energy efficiency, and a shift to cleaner energy sources (*very high confidence*) {11.9}
- Providing access to reproductive health services (including modern family planning) to improve child and maternal health through birth spacing and reduce population growth, energy use, and consequent CAP emissions over time (*medium confidence*) {11.9}
- Shifting consumption away from animal products, especially from ruminant sources, in high-meat-consumption societies toward less CAP-intensive healthy diets (*medium confidence*) {11.9}
- Designing transport systems that promote active transport and reduce use of motorized vehicles, leading to lower emissions of CAPs and better health through improved air quality and greater physical activity (*high confidence*). {11.9}

There are important research gaps regarding the health consequences of climate change and co-benefits actions, particularly in low-income countries. There are now opportunities to use existing longitudinal data on population health to investigate how climate change affects the most vulnerable populations. Another gap concerns the scientific evaluation of the health implications of adaptation measures at community and national levels. A further challenge is to improve understanding of the extent to which taking health co-benefits into account can offset the costs of greenhouse gas mitigation strategies.

11.1. Introduction

This chapter examines what is known about the effects of climate change on human health and, briefly, the more direct impacts of climate-altering pollutants (CAPs; see Glossary) on health. We review diseases and other aspects of poor health that are sensitive to weather and climate. We examine the factors that influence the susceptibility of populations and individuals to ill health due to variations in weather and climate, and describe steps that may be taken to reduce the impacts of climate change on human health. The chapter also includes a section on health "co-benefits." Co-benefits are positive effects on human health that arise from interventions to reduce emissions of those CAPs that warm the planet or vice versa.

This is a scientific assessment based on best available evidence according to the judgment of the authors. We searched the English-language literature up to August 2013, focusing primarily on publications since 2007. We drew primarily (but not exclusively) on peer-reviewed journals. Literature was identified using a published protocol (Hosking and Campbell-Lendrum, 2012) and other approaches, including extensive consultation with technical experts in the field. We examined recent substantial reviews (e.g., Gosling et al., 2009; Bassil and Cole, 2010; Hajat et al., 2010; Huang et al., 2011; McMichael, 2013b; Stanke et al., 2013) to check for any omissions of important work. In selecting citations for the chapter, we gave priority to publications that were recent (since AR4), comprehensive, added significant new findings to the literature, and included areas or population groups that have not previously been well described or were judged to be particularly policy relevant in other respects.

We begin with an outline of measures of human health, the major driving forces that act on health worldwide, recent trends in health status, and health projections for the remainder of the 21st century.

11.1.1. Present State of Global Health

The Fourth Assessment Report (AR4) pointed to dramatic improvement in life expectancy in most parts of the world in the 20th century, and this trend has continued through the first decade of the 21st century (Wang et al., 2012). Rapid progress in a few countries (especially China) has dominated global averages, but most countries have benefited from substantial reductions in mortality. There remain sizable and avoidable inequalities in life expectancy within and between nations in terms of education, income, and ethnicity (Beaglehole and Bonita, 2008) and in some countries, official statistics are so patchy in quality and coverage that it is difficult to draw firm conclusions about health trends (Byass, 2010). Years lived with disability have tended to increase in most countries (Salomon et al., 2012).

If economic development continues as forecast, it is expected that mortality rates will continue to fall in most countries; the World Health Organization (WHO) estimates the global burden of disease (measured in disability adjusted life years per capita) will decrease by 30% by 2030, compared with 2004 (WHO, 2008a). The underlying causes of global poor health are expected to change substantially, with much greater prominence of chronic diseases and injury; nevertheless, the major infectious diseases of adults and children will remain important in some regions, particularly sub-Saharan Africa and South Asia (Hughes et al., 2011).

11.1.2. Developments Since AR4

The relevant literature has grown considerably since publication of AR4. For instance, the annual number of MEDLINE citations on climate change and health doubled between 2007 and 2009 (Hosking and Campbell-Lendrum, 2012). In addition, there have been many reviews, reports, and international assessments that do not appear in listings such as MEDLINE but include important information nevertheless, for instance, the World Development Report 2010 (World Bank, 2010) and the 2011 UN Habitat report on cities and climate change (UN-HABITAT, 2011). Since AR4, there have been improvements in the methods applied to investigate climate change and health. These include more sophisticated modeling of possible future impacts (e.g., work linking climate change, food security, and health outcomes; Nelson et al., 2010) and new methods

Box 11-1 | Weather, Climate, and Health: A Long-Term Observational Study in African and Asian Populations

Given the dearth of scientific evidence of the relationship between weather/climate and health in low- and middle-income countries, we report on a project that spans sub-Saharan Africa and Asia. The INDEPTH Network currently includes 43 surveillance sites in 20 countries. Using standardized health and demographic surveillance systems, member sites have collected up to 45 years of information on births, migrations, and deaths. Currently, there are about 3.2 million people under surveillance (Sankoh and Byass, 2012).

To study relationships between weather and health, the authors obtained daily meteorological data for 12 INDEPTH populations between 2000 and 2009, and projected future climate changes to 2100 under the SRES A1B, A3, and B1 scenarios (Hondula et al., 2012). The authors concluded the health of all the populations would be challenged by the new climatic conditions, especially later in the century. In another study from the Network, Diboulo et al. (2012) examined the relation between weather and all-cause mortality data in Burkina Faso. Relations between daily temperature and mortality were similar to those reported in many high-income settings, and susceptibility to heat varied by age and gender.

to model the effects of heat on work capacity and labor productivity (Kjellstrom et al., 2009b). Other developments include coupling of high-quality, longitudinal mortality data sets with down-scaled meteorological data, in low-income settings (e.g., through the INDEPTH Network; see Box 11-1).

Since AR4, studies of the ways in which policies to reduce greenhouse gas (GHG) emissions may affect health, or vice versa, leading to so-called "co-benefits" in the case of positive outcomes for either climate or health, have multiplied (Haines et al., 2009).

Much has been written on links between climate, socioeconomic conditions, and health—for example, related to occupational heat exposure (Kjellstrom et al., 2009b) and malaria (e.g., Gething et al., 2010; Béguin et al., 2011). There is also growing appreciation of the social upheaval and damage to population health that may arise from the interaction of large-scale food insecurity, population dislocation, and conflict (see Chapter 12).

11.1.3. Non-Climate Health Effects of Climate-Altering Pollutants

CAPs affect health in other ways than through climate change, just as carbon dioxide (CO_2) creates non-climate effects such as ocean acidification. The effects of rising CO_2 levels on calcifying marine species are well documented and the risks for coral reefs are now more closely defined than they were at the time of the AR4 (see Chapter 30). There are potential implications for human health, such as undernutrition in coastal populations that depend on local fish stocks, but, so far, links between health and ocean acidification have not been closely studied (Kite-Powell et al., 2008). CAPs such as black carbon and tropospheric ozone have substantial, direct, negative effects on human health (Wang et al., 2013; see Section 11.5.3 and Box 11-3). Although CO_2 is not considered a health-damaging air pollutant at levels experienced outside particular occupational and health-care settings, one study has reported a reduction in mental performance at 1000 ppm and above, within the range that all of humanity would experience in some extreme climate scenarios by 2100 (Satish et al., 2012).

11.2. How Climate Change Affects Health

There are three basic pathways by which climate change affects health (Figure 11-1), and these provide the organization for the chapter:

- Direct impacts, which relate primarily to changes in the frequency of extreme weather including heat, drought, and heavy rain (Section 11.4)
- Effects mediated through natural systems, for example, disease vectors, water-borne diseases, and air pollution (Section 11.5)
- Effects heavily mediated by human systems, for example, occupational impacts, undernutrition, and mental stress (Section 11.6).

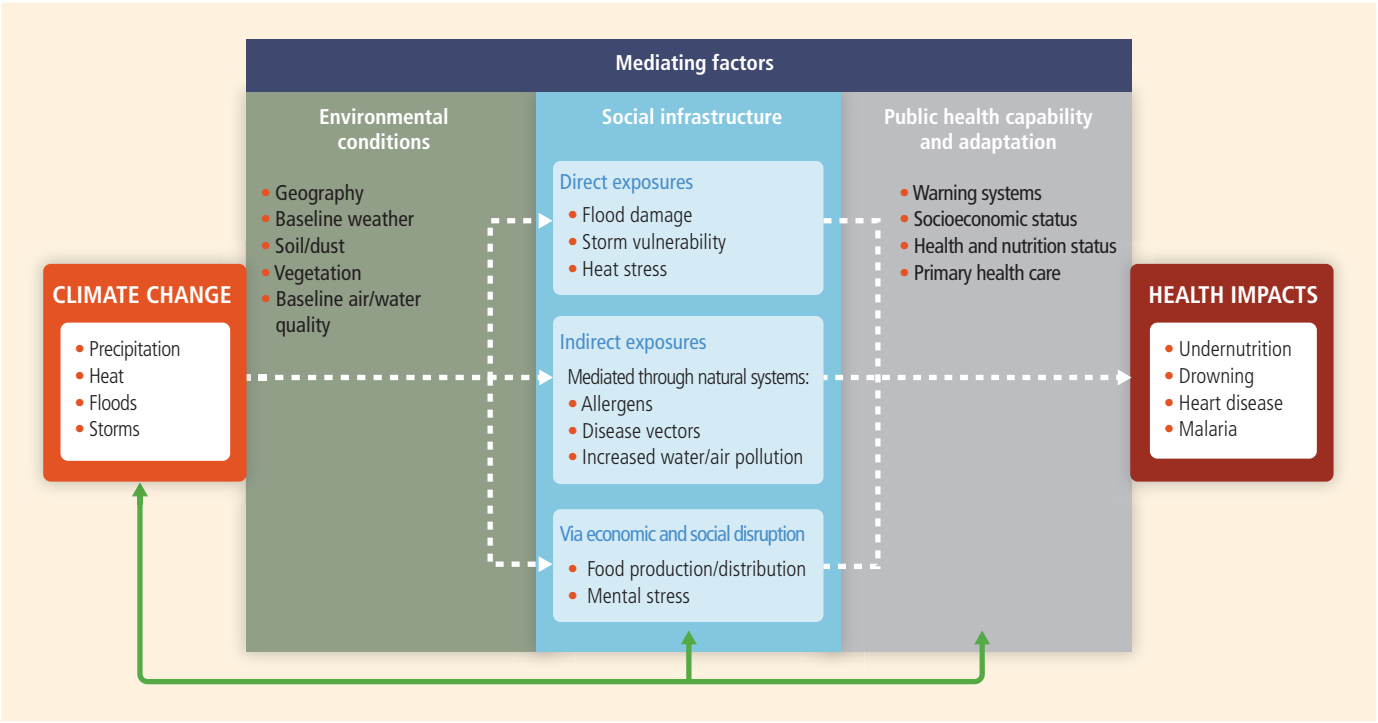


Figure 11-1 | Conceptual diagram showing three primary exposure pathways by which climate change affects health: directly through weather variables such as heat and storms; indirectly through natural systems such as disease vectors; and pathways heavily mediated through human systems such as undernutrition. The green box indicates the moderating influences of local environmental conditions on how climate change exposure pathways are manifest in a particular population. The gray box indicates that the extent to which the three categories of exposure translate to actual health burden is moderated by such factors as background public health and socioeconomic conditions, and adaptation measures. The green arrows at the bottom indicate that there may be feedback mechanisms, positive or negative, between societal infrastructure, public health, and adaptation measures and climate change itself. As discussed later in the chapter, for example, some measures to improve health also reduce emissions of climate-altering pollutants, thus reducing the extent and/or pace of climate change as well as improving local health (courtesy of E. Garcia, UC Berkeley). The examples are indicative.

The negative effects of climate change on health may be reduced by improved health services, better disaster management, and poverty alleviation, although the cost and effort may be considerable (Section 11.7). The consequences of large magnitude climate change beyond 2050, however, would be much more difficult to deal with (Section 11.8). Although there are exceptions, to a first approximation climate change acts to exacerbate existing patterns of ill health, by acting on the underlying vulnerabilities that lead to ill health even without climate change. Thus, before pursuing the three pathways in Figure 11-1, we summarize what is known about vulnerability to climate-induced illness and injury.

11.3. Vulnerability to Disease and Injury Due to Climate Variability and Climate Change

In the IPCC assessments, vulnerability is defined as the propensity or predisposition to be adversely affected (see Chapter 19 and Glossary). In this section, we consider causes of vulnerability to ill health associated with climate change and climate variability, including individual and population characteristics and factors in the physical environment.

We have outlined the causes of vulnerability separately, but in practice causes combine, often in a complex and place-specific manner. There are some factors (such as education, income, health status, and responsiveness of government) that act as generic causes of vulnerability. For example, the quality of governance—how decisions are made and put into practice—affects a community's response to threats of all kinds (Bowen et al., 2012; see Chapter 12). The background climate-related disease rate of a population is often the best single indicator of vulnerability to climate change—doubling of risk of disease in a low disease population has much less absolute impact than doubling of the disease when the background rate is high. (Note that here, and elsewhere in the chapter, we treat "risk" in the epidemiological sense: the probability that an event will occur.) But the precise causes of vulnerability, and therefore the most relevant adaptation capacities, vary greatly from one setting to another. For example, severe drought in Australia has been linked to psychological distress—but only for those residing in rural and remote areas (Berry et al., 2010). The link between high ambient temperatures and increased incidence of salmonella food poisoning has been demonstrated in many places (e.g., Zhang et al., 2010), but the lag varies from one country to another, suggesting that the mechanisms differ. Deficiencies in food storage may be the critical link in some places; food handling problems may be most important elsewhere (Kovats et al., 2004).

The 2010 World Development Report concluded that all developing regions are vulnerable to economic and social damage resulting from climate change—but for different reasons (World Bank, 2010). The critical factors for sub-Saharan Africa, for example, are the current climate stresses (in particular, droughts and floods) that may be amplified in parts of the region under climate change, sparse infrastructure, and high dependence on natural resources (see Chapter 22). Asia and the Pacific, on the other hand, are distinguished by the very large number of people living in low-lying areas prone to flooding (see Chapters 24 and 29).

11.3.1. Geographic Causes of Vulnerability

Location has an important influence on the potential for health losses caused by climate change (Samson et al., 2011). Those working outdoors in countries where temperatures in the hottest time of the year are already at the limits of thermal tolerance for part of the year will be more severely affected by further warming than workers in cooler countries (Kjellstrom et al., 2013). The inhabitants of low-lying coral atolls are very sensitive to flooding, contamination of freshwater reservoirs due to sea level rise, and salination of soil, all of which may have important effects on health (Nunn, 2009). Rural populations that rely on subsistence farming in low rainfall areas are at high risk of undernutrition and water-related diseases if drought occurs, although this vulnerability may be modified strongly by local factors, such as access to markets and irrigation facilities (Acosta-Michlik et al., 2008). Living in rural and remote areas may confer increased risk of ill health because of limited access to services and generally higher levels of social and economic disadvantage (Smith, 2008). Populations that are close to the present limits of transmission of vector-borne diseases are most vulnerable to changes in the range of transmission as a result of rising temperatures and altered patterns of rainfall, especially when disease control systems are weak (Zhou et al., 2008; Lozano-Fuentes et al., 2012.). In cities, those who live on urban heat islands are at greater risk of ill health due to extreme heat events (Stone et al., 2010; Uejio et al., 2011).

11.3.2. Current Health Status

Climate extremes may promote the transmission of certain infectious diseases, and the vulnerability of populations to these diseases will depend on the baseline levels of pathogens and their vectors. In the USA, as one example, arboviral diseases such as dengue are rarely seen after flooding, compared with the experience in other parts of the Americas. The explanation lies in the scarcity of dengue (and other pathogenic viruses) circulating in the population, before the flooding (Keim, 2008). On the other hand, the high prevalence of HIV infection in many populations in sub-Saharan Africa will tend to multiply the health risks of climate change, due to the interactions between chronic ill health, poverty, extreme weather events, and undernutrition (Ramin and McMichael, 2009). Chronic diseases such as diabetes and ischemic heart disease magnify the risk of death or severe illness associated with high ambient temperatures (Basu and Ostro, 2008; Sokolnicki et al., 2009).

11.3.3. Age and Gender

Children, young people, and the elderly are at increased risk of climate-related injury and illness (Perera, 2008). For example, adverse effects of malaria, diarrhea, and undernutrition are presently concentrated among children, for reasons of physiological susceptibility (Michon et al., 2007). In principle, children are thought to be more vulnerable to heat-related illnesses, owing to their small body mass to surface area ratio, but evidence of excess heat-related mortality in this age group is mixed (Basu and Ostro, 2008; Kovats and Hajat, 2008). Maternal antibodies acquired *in utero* provide some protection against dengue fever in the first year of life, but if infection does occur in infants it is more likely to provoke the severe hemorrhagic form of illness (Ranjit and Kissoon,

2011). Children are generally at greater risk when food supplies are restricted: households with children tend to have lower than average incomes, and food insecurity is associated with a range of adverse health outcomes among young children (Cook and Frank, 2008).

Older people are at greater risk from storms, floods, heat waves, and other extreme events (Brunkard et al., 2008), in part because they tend to be less mobile than younger adults and so find it more difficult to avoid hazardous situations and also because they are more likely to live alone in some cultures. Older people are also more likely to suffer from health conditions that limit the body's ability to respond to stressors such as heat and air pollution (Gamble et al., 2013).

The relationship between gender and vulnerability is complex. Worldwide, mortality due to natural disasters, including droughts, floods, and storms, is higher among women than men (WHO, 2011). However, there is variation regionally. In the USA, males are at greater risk of death following flooding (Jonkman and Kelman, 2005). A study of the health effects of flooding in Hunan province, China, also found an excess of flood deaths among males, often related to rural farming (Abuaku et al., 2009). In Canada's Inuit population males are exposed to dangers associated with insecure sea ice, while females may be more vulnerable to the effects of diminished food supplies (Pearce et al., 2011). In the Paris 2003 heat wave, excess mortality was greater among females overall, but there were more excess deaths among men in the working age span (25 to 64) possibly due to differential exposures to heat in occupational settings (Fouillet et al., 2006). In Bangladesh, females are more affected than males by a range of climate hazards, due to differences in prevalence of poverty, undernutrition, and exposure to water-logged environments (Neelormi et al., 2009). The effect of food insecurity on growth and development in childhood may be more damaging for girls than boys (Cook and Frank, 2008).

Pregnancy is a period of increased vulnerability to a wide range of environmental hazards, including extreme heat (Strand et al., 2012) and infectious diseases such as malaria, foodborne infections, and influenza (Van Kerkhove et al., 2011).

11.3.4. Socioeconomic Status

The poorest countries and regions are generally most susceptible to damage caused by climate extremes and climate variability (Malik et al., 2012), but wealthy countries are not immune, as shown by the deaths resulting from bushfires in Australia in 2009 (Teague et al., 2010). Also, rapid economic development may increase the risks of climate-related health issues. For instance, changes in Tibet Autonomous Region, China, including new roads and substantial in-migration may explain (along with above-average warming) the appearance and establishment in Lhasa of *Culex pipiens*, a mosquito capable of transmitting the West Nile virus (Liu et al., 2013b).

A review of global trends in tropical cyclones 1970–2009 found that mortality risk at country-level depended most strongly on three factors: storm intensity, quality of governance, and levels of poverty (Peduzzi et al., 2012). Individuals and households most vulnerable to climate hazards tend to be those with relatively low socioeconomic status (Friel et al., 2008). A study of the impacts of flooding in Bangladesh found that household risk reduced with increases in both average income and number of income sources. Poorer households were not only more severely affected by flooding, but they also took preventive action less often and received assistance after flooding less frequently than did more affluent households (Brouwer et al., 2007).

In many countries, race and ethnicity are powerful markers of health status and social disadvantage. Black Americans have been reported to be more vulnerable to heat-related deaths than other racial groups in the USA (Basu and Ostro, 2008). This may be due to a higher prevalence of chronic conditions such as overweight and diabetes (Lutsey et al., 2010), financial circumstances (e.g., lower incomes may restrict access to air conditioning during heat-waves; Ostro et al., 2010), or community-level characteristics such as higher local crime rates or disrupted social networks (Browning et al., 2006). Indigenous peoples who depend heavily on local resources, and live in parts of the world where the climate is changing quickly, are generally at greater risk of economic losses and poor health. Studies of the Inuit people, for example, show that rapid warming of the Canadian Arctic is jeopardizing hunting and many other day-to-day activities, with implications for livelihoods and well-being (Ford, 2009).

11.3.5. Public Health and Other Infrastructure

Populations that do not have access to good quality health care and essential public health services are more likely to be adversely affected by climate variability and climate change (Frumkin and McMichael, 2008). Harsh economic conditions in Europe since 2008 led to cutbacks in health services in some countries, followed by a resurgence of climate-sensitive infectious diseases including malaria (Karanikolos et al., 2013). The condition of the physical infrastructure that supports human settlements also influences health risks (this includes supply of power, provision of water for drinking and washing, waste management, and sanitation; see Chapter 8). In Cuba, a country with a well-developed public health system, dengue fever has been a persistent problem in the larger cities, due in part to the lack of a constant supply of drinking water in many neighborhoods (leading to people storing water in containers that are suitable breeding sites for the disease vector *Aedes aegypti*; Bulto et al., 2006). In New York, daily mortality spiked after a city-wide power failure in August 2003, due in part to increased exposure to heat (Anderson and Bell, 2012).

11.3.6. Projections for Vulnerability

Population growth is linked to climate change vulnerability. If nothing else changes, increasing numbers of people in locations that are already resource poor and are affected by climate risks will magnify harmful impacts. Virtually all the projected growth in populations will occur in urban agglomerations, mostly in large, low latitude hot countries in which a high proportion of the workforce is deployed outdoors with little protection from heat. About 150 million people currently live in cities affected by chronic water shortages and by 2050, unless there are rapid improvements in urban environments, the number will rise to almost a billion (McDonald et al., 2011). Under a "business as usual" scenario

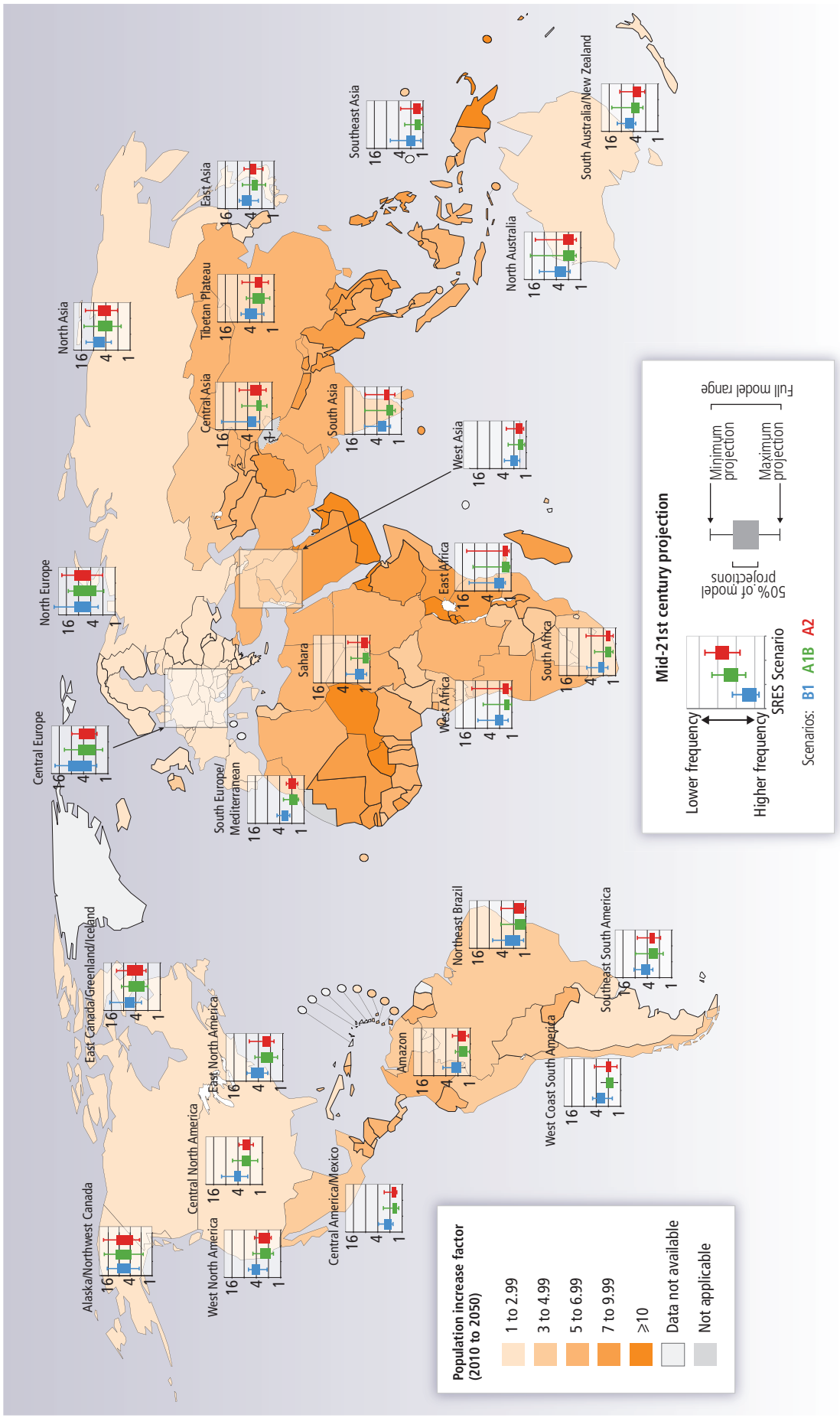


Figure 11-2 | Increasingly frequent heat extremes will combine with rapidly growing numbers of older people living in cities—who are particularly vulnerable to extreme heat. Countries are shaded according to the expected proportional increase in urban populations aged over 65 by the year 2050. Bar graphs show how frequently the maximum daily temperature that would have occurred only once in 20 years in the late 20th century is expected to occur in the mid-21st century, with lower numbers indicating more frequent events. Results are shown for three different Special Report on Emission Scenarios (SRES) scenarios (blue = B1; green = A1B, red = A2), as described in the IPCC Special Report on Emissions Scenarios, and based on 12 global climate models participating in the third phase of the Coupled Model Intercomparison Project (CMIP3). Colored boxes show the range in which 50% of the model projections are contained, and whiskers show the maximum and minimum projections from all models (WHO and WMO, 2012).

with mid-range population growth, the Organisation for Economic Co-operation and Development (OECD) projects that about 1.4 billion people will be without access to basic sanitation in 2050 (OECD, 2012). The age structure of the population also has implications for vulnerability (see Figure 11-2). The proportion aged over 60, worldwide, is projected to increase from about 10% presently to about 32% by the end of the century (Lutz et al., 2008). The prevalence of overweight and obesity, which is associated with relatively poor heat tolerance, has increased almost everywhere in the last 20 years, and in many countries the trend continues upwards (Finucane et al., 2011). It has been pointed out that the Sahel region of Africa may be particularly vulnerable to climate change because it already suffers so much stress from population pressure, chronic drought, and governmental instability (Diffenbaugh and Giorgi, 2012; Potts and Henderson, 2012).

Future trends in social and economic development are critically important to vulnerability. For instance, countries with a higher Human Development Index (HDI)—a composite of life expectancy, education, literacy, and gross domestic product (GDP) per capita—are less affected by the floods, droughts, and cyclones that take place (Patt et al., 2010). Therefore policies that boost health, education, and economic development should reduce future vulnerability. Overall, there have been substantial improvements in HDI in the last 30 years, but this has been accompanied by increasing inequalities between and within countries, and has come at the cost of high consumption of environmental resources (UNDP, 2011).

11.4. Direct Impacts of Climate and Weather on Health

11.4.1. Heat- and Cold-Related Impacts

Although there is ample evidence of the effects of weather and climate on health, there are few studies of the impacts of climate change itself. (An example: Bennett et al. (2013) reported that the ratio of summer to winter deaths in Australia increased between 1968 and 2010, in association with rising annual average temperatures.) The issue is scale, as climate change is defined in decades. Robust studies require not only extremely long-term data series on climate and disease rates, but also information on other established or potential causative factors, coupled with statistical analysis to apportion changes in health states to the various contributing factors. Wherever risks are identified, health agencies are mandated to intervene immediately, biasing long-term analyses.

Nevertheless, the connection between weather and health impacts is often sufficiently direct to permit strong inferences about cause and effect (Sauerborn and Ebi, 2012). Most notably, the association between hot days (commonly defined in terms of the percentiles of daily maximum temperature for a specified location) and increases in mortality is very robust (Honda et al., 2013). The IPCC Special Report on Extreme Events (SREX) concludes that it is *very likely* that there has been an overall decrease in the number of cold days and nights, and an overall increase in the number of warm days and nights, at the global scale. If there has been an increase in daily maximum temperatures, then it follows, in our view, that the number of heat-related deaths is *likely* to have also increased. For example, Christidis et al. (2012) concluded that it is "extremely likely (probability greater than 95%)" that anthropogenic climate change at least quadrupled the risk of extreme summer heat events in Europe in the decade 1999–2008. The 2003 heat wave was one such record event; therefore, the probability that particular heat wave can be attributed to climate change is 75% or more, and on this basis it is *likely* the excess mortality attributed to the heat wave (about 15,000 deaths in France alone (Fouillet et al., 2008)) was caused by anthropogenic climate change.

The rise in minimum temperatures may have contributed to a decline in deaths associated with cold spells; however, the influence of seasonal factors other than temperature on winter mortality suggests that the impacts on health of more frequent heat extremes greatly outweigh benefits of fewer cold days (Kinney et al., 2012; Ebi and Mills, 2013). Quantification, globally, remains highly uncertain, as there are few studies of the large developing country populations in the tropics, and these point to effects of heat, but not cold, on mortality (Hajat et al., 2010). There is also significant uncertainty over the degree of physiological, social, or technological adaptation to increasing heat over long time periods.

11.4.1.1. Mechanisms

The basic processes of human thermoregulation are well understood. If the body temperature rises above 38°C ("heat exhaustion"), physical and cognitive functions are impaired; above 40.6°C ("heat stroke"), risks of organ damage, loss of consciousness, and death increase sharply. Detailed exposure-response relationships were described long ago (Wyndham, 1969), but the relationships in different community settings and for different age/sex groups are not yet well established. The early studies are supported by more recent experimental and field studies (Ramsey and Bernard, 2000; Parsons, 2003) and meta-analysis (Bouchama et al., 2007) that show significant effects of heat stress as body temperatures exceed 40°C, and heightened vulnerability in individuals with preexisting disease.

At high temperatures, displacement of blood to the surface of the body may lead to circulatory collapse. Indoor thermal conditions, including ventilation, humidity, radiation from walls or ceiling, and the presence or absence of air conditioning, are important in determining whether adverse events occur, but these variables are seldom well-measured in epidemiological studies (Anderson et al., 2012). Biological mechanisms are less evident for other causes of death, such as suicide, that are sometimes related to high temperature (Page et al., 2007; Kim et al., 2011; Likhvar et al., 2011).

Heat waves refer to a run of hot days; precisely how many days, and how high the temperatures must rise, are defined variously (Kinney et al., 2008). Some investigators have reported that mortality increases more during heat waves than would be anticipated solely on the basis of the short-term temperature mortality relationship (D'Ippoliti et al., 2010; Anderson and Bell, 2011), although the added effect is relatively small in some series, and most evident with prolonged heat waves (Gasparrini and Armstrong, 2011). Because heat waves are relatively infrequent compared with the total number of days with temperatures greater than the optimum for that location, the effects of heat waves are only a fraction of the total impact of heat on health. Some studies

have shown larger effects of heat and heat waves earlier in the hot season (Anderson and Bell, 2011; Rocklov et al., 2011). This may be testament to the importance of acclimatization and adaptive measures, or may result from a large group in the population that is more susceptible to heat early in the season (Rocklov et al., 2009, 2011).

The extreme heat wave in Europe in 2003 led to numerous epidemiological studies. Reports from France (Fouillet et al., 2008) concluded that most of the extra deaths occurred in elderly people (80% of those who died were older than 75 years). Questions were raised at the time as to why this event had such a devastating effect (Kosatsky, 2005). It is still not clear, but one contributing factor may have been the relatively mild influenza season the year before. Recent studies have found that when the previous year's winter mortality is low, the effect of summer heat is increased (Rocklov and Forsberg, 2009; Ha et al., 2011) because mild winters may leave a higher proportion of vulnerable people (Stafoggia et al., 2009). Most studies of heat have been in high-income countries, but there has been work recently in low- and middle-income countries, suggesting heterogeneity in vulnerability by age groups and socioeconomic factors similar to that seen in higher-income settings (Bell et al., 2008b; McMichael et al., 2008; Pudpong and Hajat, 2011).

Numerous studies of temperature-related morbidity, based on hospital admissions or emergency presentations, have reported increases in events due to cardiovascular, respiratory, and kidney diseases (Hansen et al., 2008; Knowlton et al., 2009; Lin and Chan, 2009) and the impact has been related to the duration and intensity of heat (Nitschke et al., 2011).

There is evidence now that both average levels and variability in temperature are important influences on human health. The standard deviation of summer temperatures was associated with survival time in a U.S. cohort study of persons aged older than 65 years with chronic disease who were tracked from 1985 to 2006 (Zanobetti et al., 2012). Greater variability was associated with reduced survival. A study that modeled separately projected increases in temperature variability and average temperatures for six cities for 2070–2099 found that, with one exception, variability had an effect (increased deaths) over and above what was estimated from the rise in average temperatures (Gosling et al., 2009). Relevant to Section 11.5, rapid changes in temperature may also alter the balance between humans and parasites, increasing opportunities for new and resurgent diseases. The speed with which organisms adapt to changes in temperatures is, broadly speaking, a function of mass, and laboratory studies have shown that microbes respond more quickly to a highly variable climate than do their multicellular hosts (Raffel et al., 2012).

Health risks during heat extremes are greater in people who are physically active (e.g., manual laborers). This has importance for recreational activity outdoors and it is relevant especially to the impacts of climate change on occupational health (Kjellstrom et al., 2009a; Ebi and Mills, 2013; see also Section 11.6.2).

Heat also acts on human health through its effects, in conjunction with low rainfall, on fire risk. In Australia in 2009, record high temperatures, combined with long-term drought, caused fires of unprecedented intensity and 173 deaths from burns and injury (Teague et al., 2010). Smoke from forest fires has been linked elsewhere with increased mortality and morbidity (Analitis et al., 2012; see Section 11.5.3.2).

11.4.1.2. Near-Term Future

The climate change scenarios modeled by WGI AR5 project rising temperatures and an increase in frequency and intensity of heat waves (Section 2.6.1; Chapter 1) in the near-term future, defined as roughly midway through the 21st century, or the era of climate responsibility (see SPM). It is uncertain how much acclimatization may mitigate the effects on human health (Wilkinson et al., 2007a; Bi and Parton, 2008; Baccini et al., 2011; Hanna et al., 2011; Maloney and Forbes, 2011; Peng et al., 2011; Honda et al., 2013). In New York, it was estimated that acclimatization may reduce the impact of added summer heat in the 2050s by roughly a quarter (Knowlton et al., 2007). In Australia, the number of "dangerously hot" days, when core body temperatures may increase by ≥2°C and outdoor activity is hazardous, is projected to rise from the current 4 to 6 days per year to 33 to 45 days per year by 2070 (with SRES A1FI) for non-acclimatized people. Among acclimatized people, an increase from 1 to 5 days per year to 5 to 14 days per year is expected (Hanna et al., 2011).

For reasons given above, it is not clear whether winter mortality will decrease in a warmer, but more variable, climate (Kinney et al., 2012; Ebi and Mills, 2013). Overall, we conclude that the increase in heat-related mortality by mid-century will outweigh gains due to fewer cold periods, especially in tropical developing countries with limited adaptive capacities and large exposed populations (Wilkinson et al., 2007b). A similar pattern has been projected for temperate zones. A study of three Quebec cities, based on SRES A2 and B2, extended to 2099, showed an increase in summer mortality that clearly outweighed a small reduction in autumn deaths, and only slight variations in winter and spring (Doyon et al., 2008). Another study in Brisbane, Australia, using years of life lost as the outcome, found the gains associated with fewer cold days were less than the losses caused by more hot days, when warming exceeded 2°C (Huang et al., 2012).

11.4.2. Floods and Storms

Floods are the most frequently occurring type of natural disaster (Guha-Sapir et al., 2011). In 2011, 6 of the 10 biggest natural disasters were flood events, when considered in terms of both number affected (112 million people) and number of deaths (3140 people) (Guha-Sapir et al., 2011). Globally, the frequency of river flood events has been increasing, as well as economic losses, due to the expansion of population and property in flood plains (Chapter 18). There is little information on health trends attributable to flooding, except for mortality and there are large differences in mortality risk between countries (UNISDR, 2011). Mortality from flooding and storm events is generally declining, but there is good evidence that mortality risks first increase with economic development before declining (De Haen and Hemrich, 2007; Kellenberg and Mobarak, 2008; Patt et al., 2010). For instance, migration to slums in coastal cities may increase population exposure at a greater pace than can be compensated for by mitigation measures (see Chapter 10 on urban risks). Severe damaging floods in Australia in 2010–2011 and

in the northeastern USA in 2012 indicate that high-income countries may still be affected (Guha-Sapir et al., 2011).

11.4.2.1. Mechanisms

Flooding and windstorms adversely affect health through drowning, injuries, hypothermia, and infectious diseases (e.g., diarrheal disease, leptospirosis, vector-borne disease, cholera; Schnitzler et al., 2007; Jakubicka et al., 2010). Since AR4, more evidence has emerged on the long-term (months to years) implications of flooding for health. Flooding and storms may have profound effects on peoples' mental health (Neria, 2012). The prevalence of mental health symptoms (psychological distress, anxiety, and depression) was two to five times higher among individuals who reported flood water in the home compared to non-flooded individuals (2007 flood in England and Wales; Paranjothy et al., 2011). In the USA, signs of hurricane-related mental illness were observed in a follow-up of New Orleans' residents almost 2 years after Hurricane Katrina (Kessler et al., 2008). The attribution of deaths to flood events is complex; most reports of flood deaths include only immediate traumatic deaths, which means that the total mortality burden is under-reported (Health Protection Agency, 2012). There is some uncertainty as to whether flood events are associated with a longer-term (6 to 12 months) effect on mortality in the flooded population. No persisting effects were observed in a study in England and Wales (Milojevic et al., 2011), but longer-term increases in mortality were found in a rural population in Bangladesh (Milojevic et al., 2012).

11.4.2.2. Near-Term Future

Under most climate change scenarios, it is expected that more frequent intense rainfall events will occur in most parts of the world in the future (IPCC, 2012). If this happens, floods in small catchments will be more frequent, but the consequence is uncertain in larger catchments (see Chapter 3). In terms of exposure, it is expected that more people will be exposed to floods in Asia, Africa, and Central and South America (Chapter 3). Also, increases in intense tropical cyclones are *likely* in the late 21st century (WGI AR5 Table SPM.1). It has been estimated conservatively that around 2.8 billion people were affected by floods between 1980 and 2009, with more than 500,000 deaths (Doocy et al., 2013). On this basis we conclude it is *very likely* that health losses caused by storms and floods will increase this century if no adaptation measures are taken. What is not clear is how much of this projected increase can be attributed to climate change. Dasgupta et al. (2009) developed a spatially explicit mortality model for 84 developing countries and 577 coastal cities. They modeled 1-in-100 year storm-surge events, and assessed future impacts under climate change, accounting for sea level rise and a 10% increase in event intensity. In the 84 developing countries, an additional 52 million people and 30,000 km^2 of land were projected to be affected by 2100.

11.4.3. Ultraviolet Radiation

Ambient ultraviolet (UV) levels and maximum summertime day temperatures are related to the prevalence of non-melanoma skin cancers and cataracts in the eye. In one study in the USA, the number of cases of squamous cell carcinoma was 5.5% higher for every 1°C increment in average temperatures, and basal cell carcinoma was 2.9% more common with every 1°C increase. These values correspond to an increase in the effective UV dose of 2% for each 1°C (van der Leun et al., 2008). However, exposure to the sun has beneficial effects on synthesis of vitamin D, with important consequences for health. Accordingly the balance of gains and losses due to increased UV exposures vary with location, intensity of exposure, and other factors (such as diet) that influence vitamin D levels (Lucas et al., 2013). Studies of stratospheric ozone recovery and climate change project that ultraviolet radiation levels at the Earth's surface will generally return to pre-1980 levels by mid-century, and may diminish further by 2100, although there is high uncertainty around the projections (Correa et al., 2013). On the other hand, higher temperatures in countries with temperate climates may result in an increase in the time which people spend outdoors (Bélanger et al., 2009) and lead to additional UV-induced adverse effects.

11.5. Ecosystem-Mediated Impacts of Climate Change on Health Outcomes

11.5.1. Vector-Borne and Other Infectious Diseases

Vector-borne diseases (VBDs) refer most commonly to infections transmitted by the bite of blood-sucking arthropods such as mosquitoes or ticks. These are some of the best-studied diseases associated with climate change, due to their widespread occurrence and sensitivity to climatic factors (Bangs et al., 2006; Bi et al., 2007; Halide and Ridd, 2008; Wu et al., 2009). Table 11-1 summarizes what is known about the influence of weather and climate on selected VBDs.

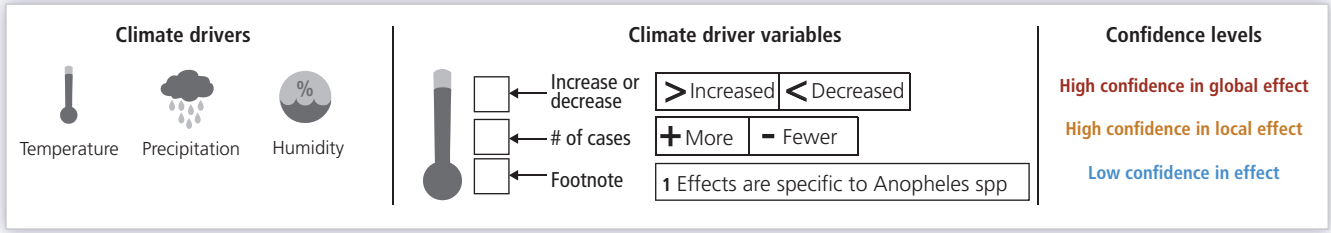
11.5.1.1. Malaria

Malaria is mainly caused by five distinct species of plasmodium parasite (*Plasmodium falciparum*, *Plasmodium vivax*, *Plasmodium malariae*, *Plasmodium ovale*, *Plasmodium knowlesi*), transmitted by Anopheline mosquitoes between individuals. In 2010 there were an estimated 216 million episodes of malaria worldwide, mostly among children younger than 5 years in the African Region (WHO, 2010). The number of global malaria deaths was estimated to be 1,238,000 in 2010 (Murray et al., 2012). Worldwide, there have been significant advances made in malaria control in the last 20 years (Feachem et al., 2010).

The influence of temperature on malaria development appears to be nonlinear, and is vector specific (Alonso et al., 2011). Increased variations in temperature, when the maximum is close to the upper limit for vector and pathogen, tend to reduce transmission, while increased variations of mean daily temperature near the minimum boundary increase transmission (Paaijmans et al., 2010). Analysis of environmental factors associated with the malaria vectors *Anopheles gambiae* and *A. funestus* in Kenya found that abundance, distribution, and disease transmission are affected in different ways by precipitation and temperature (Kelly-Hope et al., 2009). There are lag times according to the lifecycle of the vector and the parasite: a study in central China reported that malaria incidence was related to the average monthly temperature, the average

Table 11-1 | The association between different climatic drivers and the global prevalence and geographic distribution of selected vector-borne diseases observed over the period 2008-2012. Among the vector-borne diseases shown here, only dengue fever was associated with climate variables at both the global and local levels (*high confidence*), while malaria and hemorrhagic fever with renal syndrome showed a positive association at the local level (*high confidence*).

Disease	Area	Cases per year	Climate sensitivity and confidence in climate effect	Key references
Mosquito-borne diseases				
Malaria	Mainly Africa, SE Asia	About 220 million		WHO (2008); Kelly-Hope et al. (2009); Alonso et al. (2011); Omumbo et al. (2011)
Dengue	100 countries, esp. Asia Pacific	About 50 million		Beebe (2009); Pham et al. (2011); Astrom et al. (2012); Earnest et al. (2012); Descloux (2012)
Tick-borne diseases				
Tick-borne encephalitis	Europe, Russian Fed., Mongolia, China	About 10,000		Tokarevich et al. (2011)
Lyme	Temperate areas of Europe, Asia, North America	About 20,000 in USA		Bennet (2006); Ogden et al. (2008)
Other vector-borne diseases				
Hemorrhagic fever with renal syndrome (HFRS)	Global	0.15–0.2 million		Fang et al. (2010)
Plague	Endemic in many locations worldwide	About 40,000		Stenseth et al. (2006); Ari et al. (2010); Xu et al. (2011)



temperature of the previous 2 months, and the average rainfall of the current month (Zhou et al., 2010).

More work has been done since AR4 to elucidate the role of local warming on malaria transmission in the East African highlands, but this is hampered by the lack of time series data on levels of drug resistance and intensity of vector control programs. Earlier research had failed to find a clear increase in temperatures accompanying increases in malaria transmission, but new studies with aggregated meteorological data over longer periods have confirmed increasing temperatures since 1979 (Omumbo et al., 2011; Stern et al., 2011). The strongly nonlinear response to temperature means that even modest warming may drive large increases in transmission of malaria, if conditions are otherwise suitable (Pascual et al., 2006; Alonso et al., 2011). On the other hand, at relatively high temperatures modest warming may reduce the potential of malaria transmission (Lunde et al., 2013). One review (Chaves and Koenraadt, 2010) concluded that decadal temperature changes have played a role in changing malaria incidence in East Africa. But malaria is very sensitive also to socioeconomic factors and health interventions, and the generally more conducive climate conditions have been offset by more effective disease control activities. The incidence of malaria has reduced over much of East Africa (Stern et al., 2011), although increased variability in disease rates has been observed in some high-altitude areas (Chaves et al., 2012).

At the global level, economic development and control interventions have dominated changes in the extent and endemicity of malaria over the last 100 years (Gething et al., 2010). Although modest warming has facilitated malaria transmission (Pascual et al., 2006; Alonso et al., 2011), the proportion of the world's population affected by the disease has been reduced, largely due to control of *P. vivax* malaria in moderate climates with low transmission intensity. However, the burden of disease is still high and may actually be on the increase again, in some locations (WHO, 2012). For instance, locally transmitted malaria has re-emerged in Greece in association with economic hardship and cutbacks in government spending (Danis et al., 2011; Andriopoulos et al., 2013).

11.5.1.2. Dengue Fever

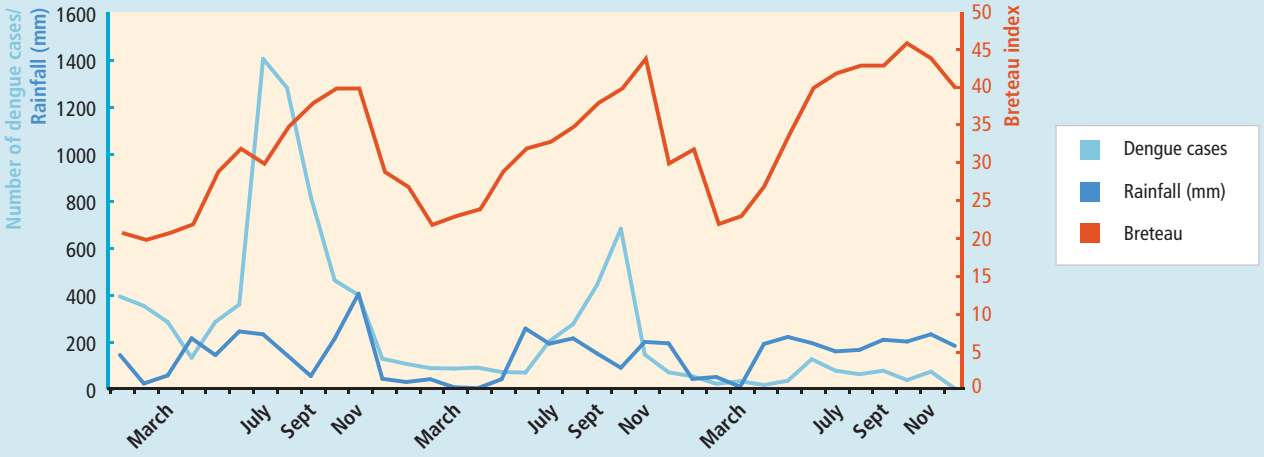
Dengue is the most rapidly spreading mosquito-borne viral disease, showing a 30-fold increase in global incidence over the past 50 years (WHO, 2013). Each year there occur about 390 million dengue infections worldwide, of which roughly 96 million manifest with symptoms (Bhatt et al., 2013). Three quarters of the people exposed to dengue are in the Asia-Pacific region, but many other regions are affected also. The first sustained transmission of dengue in Europe since the 1920s was reported in 2012 in Madeira, Portugal (Sousa et al., 2012). The disease is associated with climate on spatial (Beebe et al., 2009; Russell et al.,

Box 11-2 | Case Study: An Intervention to Control Dengue Fever

Seasonality in dengue transmission is well established in many parts of the world, and transmission occurs mostly during the wettest months of the year (Gubler and Kuno, 1997; Chadee et al., 2007). Figure 11-3 shows that about 80% of dengue fever cases in Trinidad were recorded during the wet season, a period when the *Ae. aegypti* mosquito population density was four to nine times higher than the dengue transmission threshold (Macdonald, 1956). This led to a control program that concentrated on reducing the mosquito population before the onset of the rains, by application of insecticides (temephos) into the water drums that serve as primary breeding sites of *Ae. aegypti* in the Caribbean. The one-off treatment effectively controlled the mosquito populations for almost 12 weeks after which the numbers reverted to levels observed in the untreated control areas.

Climate scenarios that extend to 2071–2100 project changes in the intensity and frequency of rainfall events in the Caribbean (Campbell et al., 2011). In these scenarios, there is greater variability in rainfall patterns during November to January, with the northern Caribbean region receiving more rainfall than in the southern Caribbean (Campbell et al., 2011). There may be water shortages during drought periods, and flooding after episodes of heavy rainfall, both of which affect the breeding habitats of *Ae. aegypti* and *Ae. albopictus*. Vector control strategies will need to be planned and managed astutely to systematically reduce mosquito populations.

(a) Rainfall, Breteau index, and Dengue cases, Trinidad (2002–2004)



(b) Efficacy of pre-seasonal treatment with temephos on *Aedes aegypti* ovitrap egg counts in Curepe (treatment) and St. Joseph (control), Trinidad (2003)

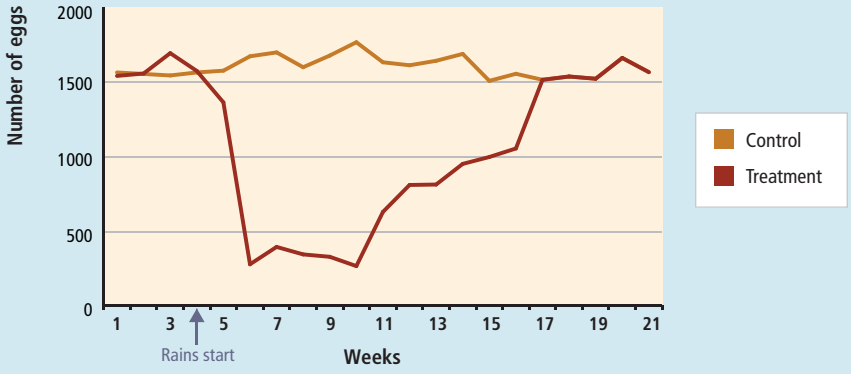


Figure 11-3 | (a) Rainfall, Breteau index (number of water containers with *Ae. aegypti* larvae per 100 houses), and dengue fever cases, Trinidad (2002–2004). Rainfall was found to be significantly correlated with an increase in the *Ae. aegypti* population and dengue fever incidence, with a clearly defined "dengue season" between June and November over two years of the study (Chadee et al., 2007). b) Efficacy of pre-seasonal treatment with temephos on *Ae. aegypti* ovitrap egg counts in Curepe (treatment) and St. Joseph (control), Trinidad (2003). Evidence of the efficacy of the pre-seasonal larval control through focal treatment of *Ae. aegypti* population is provided. Treatment at the onset of the rainy season can effectively prevent the rapid increase in *Ae. aegypti* populations and therefore suppress the onset of dengue transmission (Chadee, 2009).

2009; Li et al., 2011), temporal (Hii et al., 2009; Hsieh and Chen, 2009; Herrera-Martinez and Rodriguez-Morales, 2010; Gharbi et al., 2011; Pham et al., 2011; Descloux et al., 2012; Earnest et al., 2012) and spatiotemporal (Chowell et al., 2008, 2011; Lai, 2011) scales.

The principal vectors for dengue, Aedes aegypti and Ae. albopictus, are climate sensitive. Over the last 2 decades, climate conditions have become more suitable for albopictus in some areas (e.g., over central northwestern Europe) but less suitable elsewhere (e.g., over southern Spain) (Caminade et al., 2012). Distribution of Ae. albopictus in northwestern China is highly correlated with annual temperature and precipitation (Wu et al., 2011). Temperature, humidity, and rainfall are positively associated with dengue incidence in Guangzhou, China, and wind velocity is inversely associated with rates of the disease (Lu and Lin, 2009; Li et al., 2011). Several studies in Taiwan reported that typhoons remain an important factor affecting vector population and dengue fever (Hsieh and Chen, 2009; Lai, 2011). Typhoons result in extreme rainfall, high humidity, and water pooling, and may generate fresh mosquito breeding sites. A study in Dhaka, Bangladesh, reported increased rates of admissions to hospital due to dengue with both high and low river levels (Hashizume and Dewan, 2012). In some circumstances, it is apparent that heavy precipitation favors the spread of dengue fever, but drought can also be a cause if households store water in containers that provide suitable mosquito breeding sites (Beebe et al., 2009; Padmanabha et al., 2010).

11.5.1.3. Tick-Borne Diseases

Tick-borne encephalitis (TBE) is caused by tick-borne encephalitis virus, and is endemic in temperate regions of Europe and Asia. Lyme disease is an acute infectious disease caused by the spirochaete bacteria *Borrelia burgdorferi* and is reported in Europe, the USA, and Canada. *Borrelia* is transmitted to humans by the bite of infected ticks belonging to a few species of the genus *Ixodes* ("hard ticks"). Many studies have reported associations between climate and tick-borne diseases (Okuthe and Buyu, 2006; Lukan et al., 2010; Tokarevich et al., 2011; Andreassen et al., 2012; Estrada-Peña et al., 2012; Jaenson et al., 2012). In North America, there is good evidence of northward expansion of the distribution of the tick vector (*Ixodes scapularis*) in the period 1996–2004 based on an analysis of active and passive surveillance data (Ogden et al., 2010). However, there is no evidence so far of any associated changes in the distribution in North America of human cases of tick-borne diseases.

There was a marked rise in TBE cases from the 1970s in central and Eastern Europe. Spring-time daily maximum temperatures rose in the late 1980s, sufficient to encourage transmission of the TBE virus. For instance, in the Czech Republic, between 1970 and 2008, there were signs of lengthening transmission season and higher altitudinal range in association with warming (Kriz et al., 2012). However variations in illness rates across the region demonstrate that climate change alone cannot explain the increase. Socioeconomic changes (including changes in agriculture and recreational activities) have affected patterns of disease in Europe (Sumilo et al., 2008; Randolph, 2010). The complex ecology of tick-borne diseases such as Lyme disease and TBE make it difficult to attribute particular changes in disease frequency and distribution to specific environmental factors such as climate (Gray et al., 2009).

11.5.1.4. Other Vector-Borne Diseases

Hemorrhagic fever with renal syndrome (HFRS) is a zoonosis caused by the Hanta virus, and leads to approximately 200,000 hospitalized cases each year. The incidence of this disease has been associated with temperature, precipitation, and relative humidity (Pettersson et al., 2008; Fang et al., 2010; Liu et al., 2011). Plague, one of the oldest diseases known to humanity, persists in many parts of the world. Outbreaks have been linked to seasonal and interannual variability in climate (Stenseth et al., 2006; Nakazawa et al., 2007; Holt et al., 2009; Xu et al., 2011; MacMillan et al., 2012). Chikungunya fever is a climate-sensitive mosquito-transmitted viral disease (Anyamba et al., 2012), first identified in Africa, now present also in Asia, and the disease has recently emerged in parts of Europe (Angelini et al., 2008). The incidence in China of Japanese encephalitis, another mosquito-borne viral disease, is correlated with temperature and rainfall, especially during the warmer months of the year (Bai et al., 2013). In West Africa, outbreaks of Rift Valley Fever, an acute viral disease affecting humans and domestic animals, are linked to within-season variability in rainfall (Caminade et al., 2011).

11.5.1.5. Near-Term Future

Using the A1B climate change scenario, Béguin et al. (2011) projected the population at risk of malaria to 2030 and 2050. With GDP per capita held constant at 2010 values, the model projected 5.2 billion people at risk in 2050, out of a predicted global population of 8.5 billion. Keeping climate constant, and assuming strong economic growth allied with social development ("best case"), the model projected 1.74 billion people at risk (approximately half the present number at risk) in 2050. Factoring in climate change would increase the "best case" estimate of the number of people at risk of malaria in 2050 to 1.95 billion, which is 200 million more than if disease control efforts were not opposed by higher temperatures and shifts in rainfall patterns.

There are no recent studies that project the return of established malaria to North America or Europe, where it was once prevalent. However, suitable vectors for *P. vivax* malaria abound in these parts of the world, and recent experience in southern Europe demonstrates how rapidly the disease may reappear if health services falter (Bonovas and Nikolopoulos, 2012).

A systematic review of research on the distribution of dengue and possible influence of climate change (Van Kleef et al., 2010) concluded that the area of the planet that was climatically suitable for dengue would increase under most scenarios, but it was not possible to project the impact on disease incidence. Åström et al. (2012) estimated the population at risk out to the year 2050. The study was based on routine disease reports, surveys, population projections, estimates of GDP growth, and the A1B scenario for climate change. Assuming high GDP growth that benefits all populations, the number exposed to dengue in 2050 falls to 4.46 billion; that is, the adverse effects of climate change are balanced by the beneficial outcomes of development. This study considered only the margins of the geographic distribution of dengue (where economic development has its strongest effect) and did not examine changes in intensity of transmission in areas where the disease is already established.

Kearney (2009) used biophysical models to examine the potential extension of vector range in Australia. He predicted that climate change would increase habitat suitability throughout much of Australia. Changes in water storage as a response to a drier climate may be an indirect pathway, through which climate change affects mosquito breeding (Beebe et al., 2009).

11.5.2. Food- and Water-Borne Infections

Human exposure to climate-sensitive pathogens occurs by ingestion of contaminated water or food; incidental ingestion during swimming; or by direct contact with eyes, ears, or open wounds. Pathogens in water may be zoonotic in origin, concentrated by bivalve shellfish (e.g., oysters), or deposited on irrigated food crops. Pathogens of concern include enteric organisms that are transmitted by the fecal oral route and also bacteria and protozoa that occur naturally in aquatic systems. Climate may act directly by influencing growth, survival, persistence, transmission, or virulence of pathogens; indirect influences include climate-related perturbations in local ecosystems or the habitat of species that act as zoonotic reservoirs.

11.5.2.1. Vibrios

Vibrio is a genus of native marine bacteria that includes a number of human pathogens, most notably *V. cholerae* which causes cholera. Cholera may be transmitted by drinking water or by environmental exposure in seawater and seafood; other *Vibrio* species are solely linked to seawater and shellfish. These include *V. parahaemolyticus* and *V. vulnificus*, with *V. alginolyticus* emerging in importance (Weis, 2011). Risk of infection is influenced by temperature, precipitation, and accompanying changes in salinity due to freshwater runoff, addition of organic carbon or other nutrients, or changes in pH. These factors all affect the spatial and temporal range of the organism and also influence exposure routes (e.g., direct contact or via seafood). In countries with endemic cholera, there appears to be a robust relationship between temperature and the disease (Islam, 2009; Paz, 2009; Reyburn et al., 2011). In addition, heavy rainfall promotes the transmission of pathogens when there is not secure disposal of fecal waste. An unequivocal positive relationship between *Vibrio* numbers and sea surface temperature in the North Sea has been established by DNA analyses of formalin-fixed samples collected over a 44-year period (Vezzulli et al., 2012). Cholera outbreaks have been linked to variations in temperature and rainfall, and other variables including sea and river levels, sea chlorophyll and cyanobacteria contents, and Indian Ocean Dipole (IOD) and El Niño-Southern Oscillation (ENSO) events (de Magny et al., 2008; Hashizume, 2008; Bompangue et al., 2011; Reyburn et al., 2011; Rinaldo et al., 2012).

11.5.2.2. Other Parasites, Bacteria, and Viruses

Rates of diarrhea have been associated with high temperatures (Kolstad and Johansson, 2011). Mostly, however, neither the specific causes of the diarrheal illness are known, nor the mechanism for the association with temperature. Exceptions include *Salmonella* and *Campylobacter*, among the most common zoonotic food- and water-borne bacterial pathogens worldwide, which both show distinct seasonality in infection and higher disease rates at warmer temperatures. The association between climate (especially temperature) and non-outbreak ("sporadic") cases of salmonellosis may, in part, explain seasonal and latitudinal trends in diarrhea (Lake, 2009).

Among the enteric viruses, there are distinct seasonal patterns in infection that can be related indirectly to temperature. Enterovirus infections in the USA peak in summer and fall months (Khetsuriani et al., 2006). After controlling for seasonality and interannual variations, hand, foot, and mouth disease (caused by coxsackievirus A16 and enterovirus 71) shows a linear relationship with temperature in Singapore, with a rapid rise in incidence when the temperature exceeds 32°C (Hii et al., 2011). However, it is not clear what the underlying driver is and if temperature is confounded by other seasonal factors.

Temperature is directly linked with risk of enteric disease in Arctic communities, as melt of the permafrost hastens transport of sewage (which is often captured in shallow lagoons) into groundwater, drinking water sources, or other surface waters (Martin et al., 2007). In addition, thawing may damage drinking water intake systems (for those communities with such infrastructure) (Hess, 2008).

Rainfall has also been associated with enteric infections. Bacterial pathogens are more likely to grow on produce crops (e.g., lettuce) in simulations of warmer conditions (Liu et al., 2013a), and become attached to leafy crops under conditions of both flooding and drought (Ge et al., 2012). This latter pattern is reflected in patterns of illness (Bandyopadhyay et al., 2012). Higher concentrations of enteric viruses have been reported frequently in drinking water and recreational water following heavy rainfall (Delpla et al., 2009).

Worldwide, rotavirus infections caused about 450,000 deaths in children younger than 5 years old in 2008 (Tate et al., 2012). There are seasonal peaks in the number of cases in temperate and subtropical regions but less distinct patterns are seen within 10° latitude of the equator (Cook et al., 1990). Variations in the timing of peak outbreaks between countries or regions (Turcios et al., 2006; Atchison et al., 2010) and variations with time in the same country (Dey et al., 2010) have been attributed to fluctuations in the number and seasonality of births (Pitzer et al., 2009, 2011). While vaccination against rotavirus is expected to reduce the total burden of disease, it may also increase seasonal variation (Tate et al., 2009; Pitzer et al., 2011).

Harmful algal blooms can be formed by (1) dinoflagellates that cause outbreaks of paralytic shellfish poisoning, ciguatera fish poisoning, and neurotoxic shellfish poisoning; (2) cyanobacteria that produce toxins causing liver, neurological, digestive, and skin diseases; and (3) diatoms that can produce domoic acid, a potent neurotoxin that is bioaccumulated in shellfish and finfish (Erdner et al., 2008). Increasing temperatures promote bloom formation in both freshwater (Paerl et al., 2011) and marine environments (Marques et al., 2010; see Chapter 5). Increasing temperature favored growth of toxic over non-toxic strains of *Microcystis* in lakes in the USA (Davis et al., 2009). Projections of toxin-producing blooms in Puget Sound using an A1B scenario suggest that by the end of the century the "at risk" period may begin 2 months earlier and last up to 1 month longer than at present (Moore et al., 2011).

11.5.2.3. Near-Term Future

Kolstad and Johansson (2011) projected an increase of 8 to 11% in the risk of diarrhea in the tropics and subtropics in 2039 due to climate change, using the A1B scenario and 19 coupled atmosphere-ocean climate models from CMIP3. This study did not account for future changes in economic growth and social development. Application of down-scaled climate change models showed that overflows of sewage into Chicago's watersheds would increase by 50 to 120% by 2100, as a result of more frequent and intense rainfall (Patz et al., 2008). In Botswana, if hot, dry conditions begin earlier in the year, and are prolonged, as projected by down-scaled climate scenarios, the present dry season peak in diarrheal disease may be amplified (Alexander et al., 2013). However, the same analysis projected that incidence of diarrheal disease in the wet season would decline. Zhou et al. (2008) studied the effect of climate on transmission of schistosomiasis due to *S. japonicum* in China. They concluded that an additional 784,000 km^2 would become suitable for schistosomiasis transmission in China by 2050, as the mid-winter freezing line moves northward (Figure 11-4).

Mangal et al. (2008) constructed a mechanistic model of the transmission cycle of another species, *S. mansoni*, and reported a peak in the worm burden in humans at an ambient temperature of 30°C, falling sharply as temperature rises to 35°C. The authors attribute this to the increasing mortality of both the snails and the water-borne intermediate forms of the parasite, and noted that worm burden is not directly linked to the prevalence of schistosomiasis.

11.5.3. Air Quality

Nearly all the non-CO_2 climate-altering pollutants (see WGI AR5 Chapters 7 and 8) are health damaging, either directly or by contributing to secondary pollutants in the atmosphere. Thus, like the ocean acidification

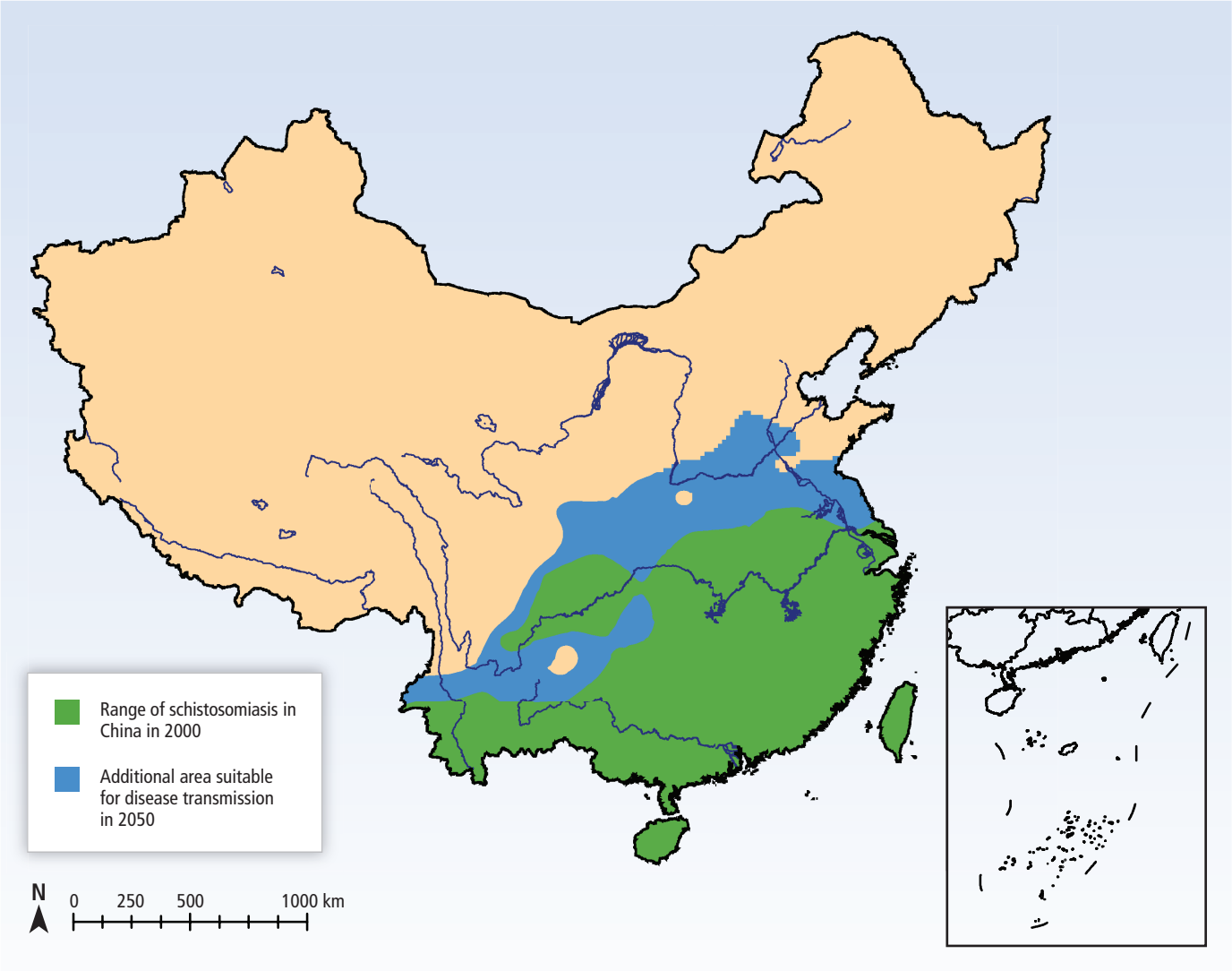


Figure 11-4 | Effect of rising temperatures on the area in which transmission of Schistosomiasis japonica may occur. Green area denotes the range of schistosomiasis in China in 2000. The blue area shows the additional area suitable for disease transmission in 2050. Based on a biology-driven model including parasite (*Schistosoma japonicum*) and snail intermediate host (*Oncomelania hupensis*) and assuming average temperatures in China in mid-winter (January) increase by 1.6°C in 2050, compared with 2000 (adapted from Zhou et al., 2008).

Box 11-3 | Health and Economic Impacts of Climate-Altering Pollutants Other than CO_2

Although other estimates of the global health impacts of human exposures to particle and ozone pollution have been published in recent years (e.g., UNEP, 2011), the most comprehensive was the Comparative Risk Assessment carried out as part of the 2010 Global Burden of Disease Project (Lim et al., 2012). It found that the combined health impact of the household exposures to particle air pollution from poor combustion of solid cooking fuels, plus general ambient pollution, was about 6.8 million premature deaths annually, with about 5% overlapping, that is, coming from the contribution to general ambient pollution of household fuels. It also found that about 150,000 premature deaths could be attributed to ambient ozone pollution. Put into terms of disability-adjusted life years (DALYs), particle air pollution was responsible for about 190 million lost DALYs in 2010, or about 7.6% of all DALYs lost. This burden puts particle air pollution among the largest risk factors globally, far higher than any other environmental risk and rivaling or exceeding all of the five dozen risk factors examined, including malnutrition, smoking, high blood pressure, and alcohol.

The economic impact of this burden is difficult to assess as evaluation methods vary dramatically in the literature. Most in the health field prefer to consider some version of a lost healthy life year as the best metric although the economics literature often uses willingness to pay for avoiding a lost life (Jamison et al., 2006). Another difficulty is that any valuation technique that weights the economic loss according to local incomes per capita will value health effects in rich countries more than in poor countries, which would seem to violate some of the premises of a global assessment; see WGIII AR5 Chapter 3 for more discussion. Here, however, we will use the mean global income per capita (approximately US$10,000 in 2010) to scope out the scale of the impact globally without attempting to be specific by country or region.

The WHO CHOICE approach for evaluating what should be spent on health interventions indicates that one annual per capita income per DALY is a reasonable upper bound (WHO, 2009a). This would imply that the total lost economic value from global climate-altering pollutants in the form of particles is roughly US$1.9 trillion, in the sense that the world ought to be willing to pay this much to reduce it. This is about 2.7% of the global economy (approximately US$70 trillion in 2010).

On the one hand, this shows that global atmospheric pollution already has a major impact on the health and economic well-being of humanity today, due mainly to the direct effects rather than those mediated through climate. If CO_2 is not controlled and climate change continues to intensify while air pollutant controls become more stringent, the climate impacts will become more prominent. The quite different time scales for the two types of impacts make comparisons difficult, however.

Air pollution reductions do not always promote the twin goals of protecting health and climate but can pose trade-offs. All particles are dangerous for health, for example, but some are cooling, such as sulfates, and some warming, such as black carbon (Smith et al., 2009). Indeed elimination of all anthropogenic particles in the atmosphere, a major success for health, would have only a minor net impact on climate (WGI AR5 Figure TS-6). As discussed in Section 11.9, there are nevertheless specific actions that will work toward both goals.

and ecosystem/agriculture fertilization impacts of CO_2, the other CAPs have non-climate-mediated impacts, particularly on health. Although not reviewed in detail in this assessment, the health impacts of non-CO_2 CAPs are substantial globally. See Box 11-3.

Although there is a large body of literature on the health effects of particulate air pollution (see Box 11-3), WGI indicates that there is little evidence that climate change, per se, will affect long-term particle levels in a consistent way (WGI AR5 Section 11.3.5 and Annex II). Thus, we focus here on chronic ozone exposures, which are found by WGI to be enhanced in some, but not all, scenarios of future climate change (WGI AR5 TS.5.4.8).

11.5.3.1. Long-Term Outdoor Ozone Exposures

Tropospheric ozone is formed through photochemical reactions that involve nitrogen oxides (NO_x), carbon monoxide (CO), methane (CH_4), and volatile organic compounds (VOCs) in the presence of sunlight and elevated temperatures (WGI AR5 Chapter 8). Therefore, if temperatures

rise, many air pollution models (Ebi and McGregor, 2008; Tsai et al., 2008; Chang et al., 2010; Polvani et al., 2011) project increased ozone production especially within and surrounding urban areas (Hesterberg et al., 2009). Enhanced temperature also accelerates destruction of ozone, and the net direct impact of climate change on ozone concentrations worldwide is thought to be a reduction (WGI AR5 TS.5.4.8). Some WGI (TS.5.4.8) scenarios, however, indicate tropospheric ozone may rise from additional CH_4 emissions stimulated by climate change. Models also show that local variations can have a different sign to the global one (Selin et al., 2009).

Even small increases in atmospheric concentrations of ground-level ozone may affect health (Bell et al., 2006; Ebi and McGregor, 2008; Jerrett et al., 2009). For instance, Bell et al. (2006) found that levels that meet the USEPA 8-hour regulation (0.08 ppm over 8 hours) were associated with increased risk of premature mortality. There is a lack of association between ozone and premature mortality only at very low concentrations (from 0 to ~10 ppb) but the association becomes positive and approximately linear at higher concentrations (Bell et al., 2006; Ebi and McGregor, 2008; Jerrett et al., 2009). In an analysis of 66 U.S. cities with 18 years of follow-up (1982–2000), tropospheric ozone levels were found to be significantly associated with cardiopulmonary mortality (Smith et al., 2009). See also the global review by WHO, which includes data from developing countries (WHO, 2006).

11.5.3.2. Acute Air Pollution Episodes

Wildfires, which occur more commonly following heat waves and drought, release particulate matter and other toxic substances that may affect large numbers of people for days to months (Finlay et al., 2012; Handmer et al., 2012). During a fire near Denver (USA) in June 2009, 1-hour concentrations of particulate matter with aerodynamic diameter <10 µm (PM_{10}) and particulate matter with aerodynamic diameter <2.5 µm ($PM_{2.5}$) reached 370 µg m^{-3} and 200 µg m^{-3}, and 24-hour average concentrations reached 91 µg m^{-3} and 44 µg m^{-3} (Vedal and Dutton, 2006), compared to the 24-hour WHO Air Quality Guidelines (AQGs) for these pollutants of 50 µg m^{-3} and 25 µg m^{-3}, respectively. One study of worldwide premature mortality attributable to air pollution from forest fires estimated there were 339,000 deaths per year (range 260,000 to 600,000) (Johnston et al., 2012). The regions most affected are sub-Saharan Africa and Southeast Asia (Johnston et al., 2012). Extremely high levels of PM_{10} were observed in Moscow due to forest fires caused by a heat wave in 2010. Daily mean temperatures in Moscow exceeded the respective long-term averages by 5°C or more for 45 days. Ten new temperature records were established in July and nine in August, based on measurements since 1885, and an anti-cyclone in the Moscow region prevented dispersion of air pollutants. The highest 24-hour pollution levels recorded in Moscow during these conditions were between 430 and 900 µg m^{-3} PM_{10} most days, but occasionally reached 1500 µg m^{-3}. The highest 24-hour CO concentration was 30 mg m^{-3} compared to the WHO AQGs of 7 mg m^{-3}, and the levels of formaldehyde, ethyl benzene, benzene, toluene, and styrene were also increased (State Environmental Institution "Mosecomonitoring," 2010).

There may be an interaction of tropospheric ozone and heat waves. Dear et al. (2005) modeled the daily mortality due to heat and exposure to ozone during the European summer heat wave of 2003 and found that possibly 50% of the deaths could have been associated with ozone exposure rather than the heat itself.

11.5.3.3. Aeroallergens

Allergic diseases are common and some are climate sensitive. Warmer conditions generally favor the production and release of airborne allergens (such as fungal spores and plant pollen) and, consequently, there may be an effect on asthma and other allergic respiratory diseases such as allergic rhinitis, as well as effects on conjunctivitis and dermatitis (Beggs, 2010). Children are particularly susceptible to most allergic diseases (Schmier and Ebi, 2009). Increased release of allergens may be amplified if higher CO_2 levels stimulate plant growth. Visual monitoring and experiments have shown that increases in air temperature cause earlier flowering of prairie tallgrass (Sherry et al., 2007). Droughts and high winds may produce windborne dust and other atmospheric materials, which contain pollen and spores, and transport these allergens to new regions.

Studies have shown that increasing concentrations of grass pollen lead to more frequent ambulance calls due to asthma symptoms, with a time lag of 3 to 5 days (Heguy et al., 2008). Pollen levels have also been linked to hospital visits with rhinitis symptoms (Breton et al., 2006). A cross-sectional study in the three climatic regions of Spain documented a positive correlation between the rate of child eczema and humidity, and negative correlation between child eczema and air temperature or the number of sunshine hours (Suarez-Varela et al., 2008).

11.5.3.4. Near-Term Future

It is projected by WGI that climate change could affect future air quality, including levels of photochemical oxidants and, with much less certainty, fine particles ($PM_{2.5}$). If this occurs, there will be consequences for human health (Bell et al., 2007; Dong et al., 2011; Chang et al., 2012; Lepeule et al., 2012; Meister et al., 2012; West et al., 2013). High temperatures may also magnify the effects of ozone (Ren et al., 2008; Jackson et al., 2010). Increasing urbanization, use of solid biomass fuels, and industrial development in the absence of emission controls could also lead to increases in ozone chemical precursors (Selin et al., 2009; Wilkinson et al., 2009).

Most post-2006 studies on the projected impacts of future climate change on air pollution-related morbidity and mortality have focused on ozone in Europe, the USA, and Canada (Bell et al., 2007; Selin et al., 2009; Tagaris et al., 2009). Projections are rare for other areas of the world, notably the developing countries where air pollution is presently a serious problem and is expected to worsen unless controls are strengthened.

Higher temperatures may magnify the effects of air pollutants like ozone, although estimates of the size of this effect vary (Ren et al., 2008; Jackson et al., 2010). In general, all-cause mortality related to ozone is expected to increase in the USA and Canada (Bell et al., 2007; Tagaris et al., 2009; Jackson et al., 2010; Cheng et al., 2011). Under a scenario in

which present air quality legislation is rolled out everywhere, premature deaths due to ozone would be wound back in Africa, South Asia, and East Asia. Under a maximum feasible CO_2 reduction scenario related to A2, it is projected that 460,000 premature ozone-related deaths could be avoided in 2030, mostly in South Asia (West et al., 2007a). All-cause mortality, however, is not the best metric for comparing air pollution health impacts across regions, given that background disease conditions vary so widely. HIV deaths and malaria deaths, which are prominent in sub-Saharan Africa, for example, are not expected to increase from air pollution exposures in the same way as deaths from cardiovascular disease that dominate other regions.

A study that investigated regional air quality in the USA in 2050, using a down-scaled climate model (Goddard Institute for Space Studies, Global Climate Model), concluded there would be about 4000 additional annual premature deaths due to increased exposures to $PM_{2.5}$ (Tagaris et al., 2009). Air pollutant-related mortality increases are also projected for Canada, but in this case they are largely driven by the effects of ozone (Cheng et al., 2011). On the basis of the relation of asthma to air quality in the last decade (1999–2010), Thompson et al. (2012) anticipate that the prevalence of asthma in South Africa will increase substantially by 2050. Sheffield et al. (2011), applying the SRES A2 scenario, projected a median 7.3% increase in summer ozone-related asthma emergency department visits for children (0 to 17 years) across New York City by the 2020s compared to the 1990s.

11.6. Health Impacts Heavily Mediated through Human Institutions

11.6.1. Nutrition

Nutrition is a function of agricultural production (net of post-harvest wastes and storage losses), socioeconomic factors, such as food prices and access, and human diseases, especially those that affect appetite, nutrient absorption, and catabolism (Black et al., 2008; Lloyd et al., 2011). All three may be influenced by climate but only agricultural production has been modeled in a climate impacts framework. Here we use the terms undernutrition, which is a health outcome, and undernourishment, which reflects national (post-trade) calories available for human consumption, and is expressed as estimated percent of the population receiving "insufficient" calories. We do not use the term "malnutrition," as it includes overnutrition, which is not considered here (except under co-benefits in Section 11.9). Undernutrition can be chronic, leading to stunting (low height for age), or acute, leading to wasting (low weight for height); underweight (low weight for age) is a combination of chronic and acute undernutrition.

11.6.1.1. Mechanisms

The processes through which climate change can affect human nutrition are complex (see Section 7.2.2). Higher temperatures and changes in precipitation may reduce both the quantity and quality of food harvested (e.g., Battisti and Naylor, 2009). Lobell et al. (2011b) showed for African maize that for each degree above 30°C, yields decreased by 1% under optimal rainfall conditions and by 1.7 % under drought conditions. From their systematic review of more than a thousand studies, Knox et al. (2012) drew the conclusion that "climate change is a threat to crop productivity in areas that are already food insecure." Rising temperatures may also affect food security through the impact of heat on productivity of farmers (see Section 11.6.2).

The magnitude of detected and predicted decline in land-based agricultural production due to increasing temperatures and changes in rainfall must be put in perspective to other changes, such as increase in harvests due to improved farming knowledge and technology, the amount of food fed to livestock, used for biofuels, consumed beyond baseline needs by the overnourished, or wasted in other ways (Foley et al., 2011). There is good evidence that local food price increases have negative effects on food consumption, and therefore on health (Green et al., 2013). Against this background, the global food price fluctuates, though with a recently rising trend. While the main driver is higher energy costs, amplified by speculation (Piesse and Thirtle, 2009), there is growing evidence (Auffhammer, 2011) that extreme weather events, especially floods, droughts (Williams and Funk, 2011), and heat waves, may have contributed to higher prices. All else being equal, higher prices increase the number of malnourished people. See Chapter 7 for a more detailed discussion of the impact of climate change on food production.

11.6.1.2. Near-Term Future

Since AR4 at least four studies have been published which project the effect of climate change on undernourishment and undernutrition.

Nelson et al. (2009, 2010) conducted two studies using a crop simulation model (DSSAT) and a global agricultural trade model (IMPACT 2009) to estimate crop production (with and without CO_2 enrichment), calorie availability, child underweight, and adaptation costs. The first study (Nelson et al., 2009) was carried out under the A2 emission scenario, using two General Circulation Models (GCMs): National Center for Atmospheric Research (NCAR) and Commonwealth Scientific and Industrial Research Organisation (CSIRO) and relative to a "no climate change" future. The authors found that yields of most important crops would decline in developing countries by 2050, that per capita calorie

Table 11-2 | Number of undernourished children younger than 5 years of age (in millions) in 2000 and 2050, using the National Center for Atmospheric Research (NCAR) climate model (and the A2 scenario from AR4). Results assume no effect of heat on farmers' productivity, and no CO_2 fertilization benefits. (Adapted from Nelson et al., 2009).

Scenario		South Asia	East Asia/Pacific	Europe and Central Asia	Latin America and Caribbean	Middle East/ North Africa	Sub-Saharan Africa	All developing countries
2000		75.6	23.8	4.1	7.7	3.5	32.7	147.9
2050	No climate change	52.3	10.1	2.7	5.0	1.1	41.7	113.3
	Climate change	59.1	14.5	3.7	6.4	2.1	52.2	138.5

availability would drop below levels that applied in the year 2000, and that child underweight would be approximately 20% higher (in the absence of carbon enrichment effects). That is, about 25 million children would be affected (see Table 11-2). Of note, the underweight estimates do not account for possible improvements in socioeconomic conditions between 2000 and 2050. However, it was estimated that substantial improvements would be necessary to counteract the effects of climate change. These included a 60% increase in yield growth (all crops) over baseline, 30% faster growth in animal numbers, and a 25% increase in the rate of expansion of irrigated areas. The second study by Nelson et al. used a wider range of socioeconomic and climate scenarios but health impacts were similar to the first study. Estimates of improved socioeconomic conditions were insufficient to fully offset the potential impacts of climate change: child underweight was estimated to be approximately 10% higher with climate change compared to a future without climate change.

Lloyd et al. (2011) built a model for estimating future stunting driven by two principal inputs: estimates of undernourishment (i.e., "food-related" causes of stunting) and socioeconomic conditions (i.e., "non-food-related" causes of stunting). The former were based on calorie availability estimates from Nelson et al. (2009), and the latter on GDP per capita projections and estimates of the Gini index for income distribution. They estimated that by 2050, under A2 emissions with moderate to high economic growth and compared to a future without climate change, there may be a relative increase of severe stunting of 31 to 55% across regions of sub-Saharan Africa and 61% in South Asia. It should be noted here that severe stunting carries three to four times the mortality risk of moderate stunting. In a future without climate change, undernutrition was projected to decline, leading the authors to conclude that climate change would hold back efforts to reduce child undernutrition in the most severely affected parts of the world, even after accounting for the potential benefits of economic growth.

In addition to global studies, regional projections of the impacts of climate change on undernutrition have also been carried out since AR4. Grace et al. (2012) modeled the relationship between climate variables (temperature and precipitation), food production and availability, as well as child stunting in Kenya. The authors concluded that climate change will increase the proportion of stunted children in countries such as Kenya that are dependent on rain-fed agriculture, unless there are substantial adaptation efforts, such as investment in education and agricultural technology.

Similarly, Jankowska et al. (2012) included climate, livelihood, and health variables (stunting and underweight). The authors identified a link between type of livelihood and risk of undernutrition, and climate and stunting. Applying the model to Mali, the authors projected impacts to 2025 and estimated that nearly 6 million people may experience undernutrition due to changes in climate, livelihood, and demography; three-quarter to one million of this number will be children younger than five.

In summary, we conclude that climate change will have a substantial negative impact on (1) per capita calorie availability; (2) childhood undernutrition, particularly stunting; and (3) on undernutrition-related child deaths and DALYs lost in developing countries (*high confidence*).

11.6.2. Occupational Health

Since AR4, much has been written on the effects of heat on working people (Kjellstrom et al., 2009a; Dunne et al., 2013) and on other climate-related occupational health risks (Bennett and McMichael, 2010; Schulte and Chun, 2009).

11.6.2.1. Heat Strain and Heat Stroke

Worldwide, more than half of all non-household labor-hours occur outdoors, mainly in agriculture and construction (IFAD, 2010; ILO, 2013). Individuals who are obliged to work outside in hot conditions, without access to shade, or sufficient water, are at heightened risk of heat strain (ICD code T.67, "heat exhaustion") and heat stroke. Health risks increase with the level of physical exertion. Agricultural and construction workers in tropical developing countries are therefore among the most exposed, but heat stress is also an issue for those working indoors in environments that are not temperature-controlled, and even for some workers in high-income countries such as the USA (Luginbuhl et al., 2008; see Figure 11-5). Moreover, at higher temperatures there is potential conflict between health protection and economic productivity (Kjellstrom et al., 2011): as workers take longer rests to prevent heat stress, hourly productivity goes down (Sahu et al., 2013).

11.6.2.2. Heat Exhaustion and Work Capacity Loss

There are international standards of maximum recommended workplace heat exposure and hourly rest time (e.g., ISO, 1989; Parsons, 2003) for both acclimatized and non-acclimatized people. In hot countries during the hot season, large proportions of the workforce are affected by heat, and the economic impacts of reduced work capacity may be sufficient to jeopardize livelihoods (Lecocq and Shalizi, 2007; Kjellstrom et al., 2009a, 2011; Kjellstrom and Crowe, 2011). Kjellstrom and Crow (2011) and Dunne et al. (2013) report that loss of work productivity during the hottest and wettest seasons has already occurred, at least in Asia and Africa.

11.6.2.3. Other Occupational Health Concerns

In areas where vector-borne diseases, such as malaria and dengue fever, are common, people working in fields without effective protection may experience a higher incidence of these diseases when climatic conditions favor mosquito breeding and biting (Bennett and McMichael, 2010). Increasing heat exposure in farm fields during the middle of the day may lead to more work during dawn and dusk when some of the vectors are biting humans more actively. Exposure to heat affects psychomotor, perceptual, and cognitive performance (Hancock et al., 2007) and increases risk of injuries (Ramsey, 1995). Extreme weather events and climate-sensitive infectious diseases also pose occupational risks to health workers, which may in turn undermine health protection for the wider population (WHO, 2009b). Other mechanisms include elevated occupational exposures to toxic chemical solvents that evaporate faster at higher temperatures (Bennett and McMichael, 2010) and rising temperatures reducing sea ice and increasing risk of drowning in those engaged in traditional hunting and fishing in the Arctic (Ford et al., 2008).

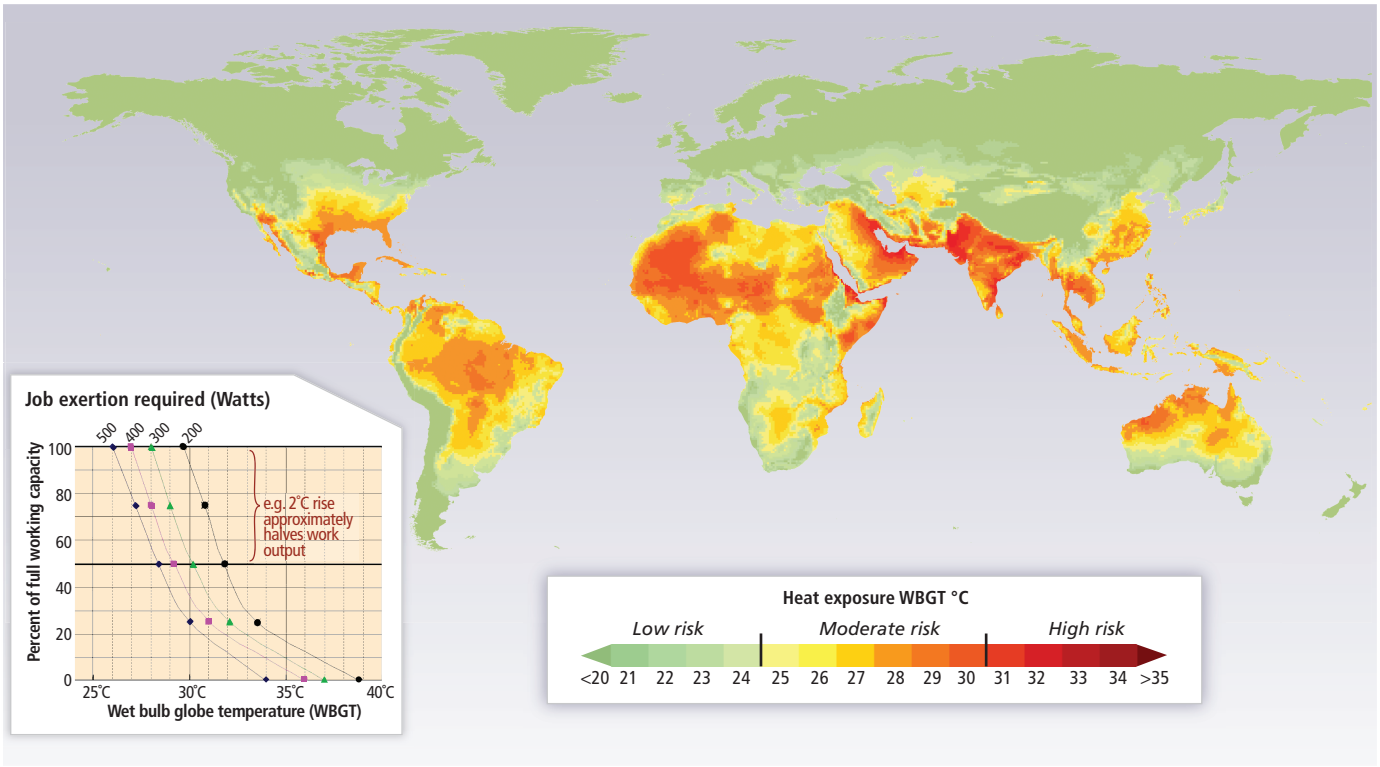


Figure 11-5 | The 1980–2009 average of the hottest months globally, measured in web bulb globe temperature (WBGT), which combines temperature, humidity, and other factors into a single index of the impact on work capacity and threat of heat exhaustion. The insert shows the International Organization for Standardization standard (ISO,1989) for heat stress in the workplace that leads to recommendations for increased rest time per hour to avoid heat exhaustion at different work levels. This is based on studies of healthy young workers and includes a margin of safety. Note that some parts of the world already exceed the level for safe work activity during the hottest month. In general, with climate change, for every 1°C that T_{max} goes up, the WBGT goes up by about 0.9°C, leading to more parts of the world being restricted for more of the year, with consequent impacts on productivity, heat exhaustion, and need for air conditioning to protect health (Lemke and Kjellstrom, 2012).

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11.6.2.4. Near-Term Future

Projections have been made of the future effects of heat on work capacity (Kjellstrom et al., 2009b; Dunne et al., 2013). Temperature and humidity were both included, and the modeling took into account the changes in the workforce distribution relating to the need for physical activity. In Southeast Asia, in 2050, the model indicates that more than half the afternoon work hours will be lost due to the need for rest breaks (Kjellstrom et al., 2013). By 2100, under RCP4.5, Dunne et al. (2013) project up to a 20% loss of productivity globally. There is an unfortunate trade-off between health impact and productivity, which creates risks for poor and disenfranchised laborers working under difficult working conditions and inflexible rules (Kjellstrom et al., 2009a, 2011; Sahu et al., 2013).

11.6.3. Mental Health

Harsher weather conditions such as floods, droughts, and heat waves tend to increase the stress on all those who are already mentally ill, and may create sufficient stress for some who are not yet ill to become so (Berry et al., 2010). Manifestations of disaster-related psychiatric trauma include severe anxiety reactions (such as post-traumatic stress) and longer-term impacts such as generalized anxiety, depression, aggression, and complex psychopathology (Ahern et al., 2005; Ronan et al., 2008).

For slow-developing events such as prolonged droughts, impacts include chronic psychological distress and increased incidence of suicide (Alston and Kent, 2008; Hanigan et al., 2012). Extreme weather conditions may have indirect effects on those with mental illness, through the impacts on agricultural productivity, fishing, forestry, and other economic activities. Disasters such as cyclones, heat waves, and major floods may also have destructive effects in cities. Here again, the mentally ill may be at risk: cities often feature zones of concentrated disadvantage where mental disorders are more common (Berry, 2007) and there is also higher risk of natural disasters (such as flooding).

In addition to effects of extreme weather events on mental health via the risk/disadvantage cycle, there may be a distressing sense of loss, known as "solastalgia," that people experience when their land is damaged (Albrecht et al., 2007) and they lose amenity and opportunity.

11.6.4. Violence and Conflict

Soil degradation, freshwater scarcity, population pressures, and other forces that are related to climate are all potential causes of conflict. The relationships are not straightforward, however, as many factors influence conflict and violence. The topic is reviewed closely in Chapter 12, which concludes that factors associated with risk of violent conflict, such as poverty and impaired state institutions, are sensitive to climate variability,

but evidence of an effect of climate change on violence is contested. Also, it is noted that populations affected by violence are particularly vulnerable to the impacts of climate change on health and social well-being.

11.7. Adaptation to Protect Health

Climate change may threaten the progress that has been made in reducing the burden of climate-related disease and injury. The degree to which programs and measures will need modification to address additional pressures from climate change will depend on the current burden of ill health; the effectiveness of current interventions; projections of where, when, and how the health burden could change with climate change; the feasibility of implementing additional programs; other stressors that could increase or decrease resilience; and the social, economic, and political context for intervention (Ebi et al., 2006).

The scientific literature on adaptation to climate change has expanded since AR4, and there are many more national adaptation plans that include health, but investment in specific health protection activities is growing less rapidly. A review by the World Health Organization in 2012 estimated that commitments to health adaptation internationally amount to less than 1% of the annual health costs attributable to climate change in 2030 (WHO Regional Office for Europe, 2013).

The value of adaptation is demonstrated by the health impacts of recent disasters associated with extreme weather and climate events, although not necessarily attributed with confidence to climate change itself. For example, approximately 500,000 people died when Cyclone Bhola (category 3 in severity) hit East Pakistan (present day Bangladesh) in 1970 (Khan, 2008). In 1991, a cyclone of similar severity caused about 140,000 deaths. In November 2007, Cyclone Sidr (category 4) resulted in approximately 3400 deaths. The population had grown by more than 30 million in the intervening period (Mallick et al., 2005). Bangladesh achieved this remarkable reduction in mortality through effective collaborations between governmental and non-governmental organizations and local communities (Khan, 2008).

Alongside improving general disaster education (greatly assisted by rising literacy rates, especially among women), the country deployed early warning systems and built a network of cyclone shelters. Early warning systems included high-technology information systems and relatively simple measures such as training volunteers to distribute warning messages by bicycle.

Efforts to adapt to the health impacts of climate change can be categorized as incremental, transitional, and transformational actions (O'Brien et al., 2012). Incremental adaptation includes improving public health and health care services for climate-related health outcomes, without necessarily considering the possible impacts of climate change. Transitional adaptation means shifts in attitudes and perceptions, leading to initiatives such as vulnerability mapping and improved surveillance systems that specifically integrate environmental factors. Transformational adaptation (see Chapter 16), which requires fundamental changes in systems, has yet to be implemented in the health sector.

11.7.1. Improving Basic Public Health and Health Care Services

Although the short time period since health adaptation options have been implemented means evidence of effectiveness in specifically reducing climate change-related impacts is currently lacking, there is abundant evidence of steps that may be taken to improve relevant public health functions (Woodward et al., 2011). This is important because the present health status of a population may be the single most important predictor of both the future health impacts of climate change and the costs of adaptation (Pandey, 2010). Most health adaptation focuses on improvements in public health functions to reduce the current adaptation deficit, such as enhancing disease surveillance, monitoring environmental exposures, improving disaster risk management, and facilitating coordination between health and other sectors to deal with shifts in the incidence and geographic range of diseases (Woodward et al., 2011).

Examples of incremental health care interventions include introduction of vaccination programs in the USA, after which seasonal outbreaks of rotavirus, a common climate-sensitive pathogen, were delayed and diminished in magnitude (Tate et al., 2009). Post-disaster initiatives also are important. For example, an assessment of actions to improve the resilience of vulnerable populations to heat waves recommended staff planning over the summer period, cooling of health care facilities, training of staff to recognize and treat heat strain, and monitoring of those in the highest risk population groups (WHO Regional Office for Europe, 2009). Ensuring essential medical supplies for care of individuals with chronic conditions, including effective post-disaster distribution, would increase the ability of communities to manage large-scale floods and storms. In Benin, one measure proposed as part of the national response to sea level rise and flooding is expanded health insurance arrangements, so that diseases such as malaria and enteric infections can be treated promptly and effectively (Dossou and Glehouenou-Dossou, 2007).

11.7.2. Health Adaptation Policies and Measures

Transitional adaptation moves beyond focusing on reducing the current adaptation deficit to considerations of how a changing climate could alter health burdens and the effectiveness of interventions (Frumkin et al., 2008). For example, maintaining and improving food safety in the face of rising temperatures and rainfall extremes depends on effective interactions between human health and veterinary authorities, integrated monitoring of food-borne and animal diseases, and improved methods to detect pathogens and contaminants in food (Tirado et al., 2010). Indicators of community functioning and connectedness also are relevant because communities with high levels of social capital tend to be more successful in disseminating health and related messages, providing support to those in need (Frumkin et al., 2008).

11.7.2.1. Vulnerability Mapping

Vulnerability mapping is being increasingly used to better understand current and possible future risks related to climate change. For example, Reid et al. (2009) mapped community determinants of heat vulnerability

in the USA. The four factors explaining most of the variance were a combination of social and environmental factors, social isolation, prevalence of air conditioning, and the proportion of the population who were elderly or diabetic. Remote-sensing technologies are now sufficiently fine-grained to map local vulnerability. For example, these technologies can be used to map surface temperatures and urban heat island effects at the neighborhood scale, indicating where city greening and other urban cooling measures could be most effective, and alerting public health authorities to populations that may be at greatest risk of heat waves (Luber and McGeehin, 2008). In another example, spatial modeling of geo-referenced climate and environmental information was used to identify characteristics of domestic malaria transmission in 2009–2012 in Greece, to guide malaria control efforts (Sudre et al., 2013). Mapping at regional and larger scales may be useful to guide adaptation actions. In Portugal, modeling of Lyme disease indicates that future conditions will be less favorable for disease transmission in the south, but more favorable in the center and northern parts of the country (Casimiro et al., 2006). This information can be used to modify surveillance programs before disease outbreaks occur. To capture a more complete picture of vulnerability, mapping exercises also could consider climate sensitivity and adaptation capacity, such as was done in an assessment of climate change and risk of poverty in Africa (Thornton et al., 2008).

11.7.3. Early Warning Systems

Early warning systems have been developed in many areas to prevent negative health impacts through alerting public health authorities and the general public about climate-related health risks. Effective early warning systems take into consideration the range of factors that can drive risk and are developed in collaboration with end users.

Components of effective early warning systems include forecasting weather conditions associated with increased morbidity or mortality, predicting possible health outcomes, identifying triggers of effective and timely response plans that target vulnerable populations, communicating risks and prevention responses, and evaluating and revising the system to increase effectiveness in a changing climate (Lowe et al., 2011). Heat wave early warning systems are being increasingly implemented, primarily in high-income countries. Of seven studies of the effectiveness of heat wave early warning systems or heat prevention activities to reduce heat-related mortality, six reported fewer deaths during heat waves after implementation of the system (Palecki et al., 2001; Weisskopf et al., 2002; Ebi et al., 2004; Tan et al., 2007; Fouillet et al., 2008; Chau et al., 2009); only Morabito et al. (2012) was inconclusive. For example, in the summer of 2006, France experienced high temperatures with about 2000 excess deaths. This was more than 4000 fewer deaths than was anticipated on the basis of what occurred in the 2003 heat wave. A national assessment attributed the lower than expected death toll to greater public awareness of the health risks of heat, improved health care facilities, and the introduction in 2004 of a heat wave early warning system (Fouillet et al., 2008). A review of the heat wave early warning systems in the 12 European countries with such plans concluded that evaluations of the effectiveness of these systems is urgently needed to inform good practices, particularly understanding which actions increase resilience (Lowe et al., 2011).

Early warning systems have been developed also for vector-borne and food-borne infections, although evidence of their effectiveness in reducing disease burdens is limited. In Botswana, an early warning system forecasts malaria incidence up to 4 months in advance based on observed rainfall; interannual and seasonal variations in climate are associated with outbreaks of malaria in this part of Africa. Model outputs include probability distributions of disease risk and measures of the uncertainty associated with the forecasts (Thomson et al., 2006). A weather-based forecasting model for dengue, developed in Singapore, predicted epidemics 13 months ahead of the peak in new cases, which gave the national control program time to increase control measures (Hii et al., 2012). A study of campylobacteriosis in the USA developed models of monthly disease risk with a very good fit in validation data sets (R^2 up to 80%) (Weisent et al., 2010).

11.7.4. Role of Other Sectors in Health Adaptation

Other sectors—including ecosystems, water supply and sanitation, agriculture, infrastructure, energy and transportation, land use management, and others—play an important part in determining the risks of disease and injury resulting from climate change.

Within the context of the EuroHEAT project, a review of public health responses to extreme heat in Europe identified transport policies, building design, and urban land use as important elements of national and municipal heat wave and health action plans (WHO Regional Office for Europe, 2009). A study examining well-established interventions to reduce the urban heat island effect (replacing bitumen and concrete with more heat-reflective surfaces, and introducing more green spaces to the city) estimated these would reduce heat-related emergency calls for medical assistance by almost 50% (Silva et al., 2010). Urban green spaces lower ambient temperatures, improve air quality, provide shade, and may be good for mental health (van den Berg et al., 2010). However, the extent to which changes in these factors reduce heat wave-related morbidity and mortality depend on location. A study in London, UK, found that built form and other dwelling characteristics more strongly influenced indoor temperatures during heat waves than did the urban health island effect (Oikonomou and Wilkinson, 2012).

A review of food aid programs indicates that a rapid response to the risk of child undernutrition, targeted to those in greatest need, with flexible financing and the capacity to rapidly scale up depending on need, may reduce damaging health consequences (Alderman, 2010). Community-based programs designed for other purposes can facilitate adaptation, including disaster risk management. In the Philippines, for example, interventions in low-income urban settings with the potential to reduce the harmful effects of climate extremes on health include savings schemes, small-scale loans, hygiene education, local control and maintenance of water supplies, and neighborhood level solid waste management strategies (Dodman et al., 2010). It is important to note that climate change adaptation in other sectors may influence health in a positive manner (e.g., re-vegetation of watersheds to improve water quality), or on occasion, exacerbate health risks (e.g., urban wetlands designed primarily for flood control may promote mosquito breeding) (Medlock and Vaux, 2011).

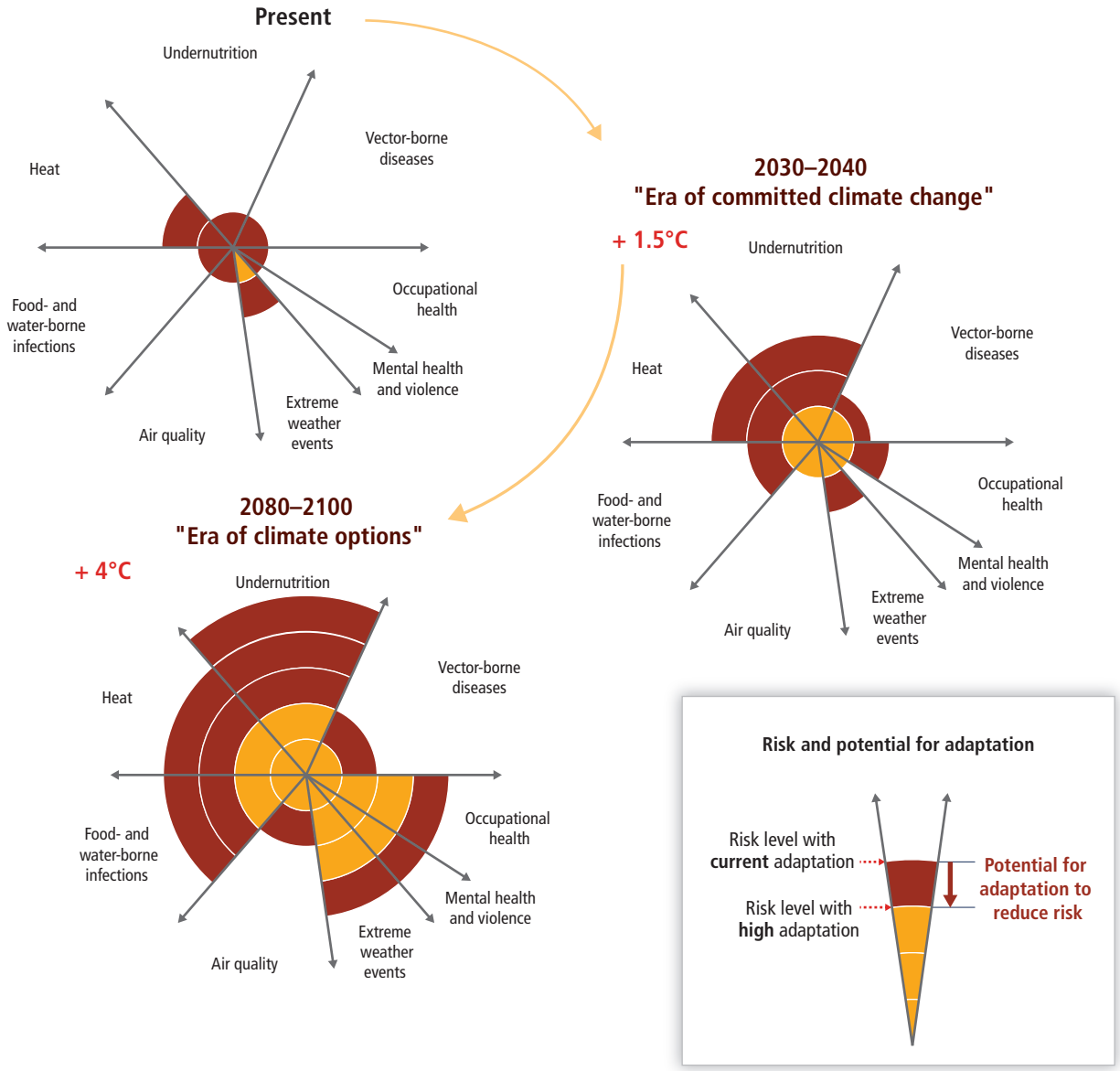

Figure 11-6 | Conceptual presentation of the health impacts from climate change and the potential for impact reduction through adaptation. Impacts are identified in eight health-related sectors based on assessment of the literature and expert judgments by authors of Chapter 11. The width of the slices indicates in a qualitative way the relative importance in terms of burden of ill health globally at present and should not be considered completely independent. Impact levels are presented for the near-term "era of committed climate change" (2030–2040), in which projected levels of global mean temperature increases do not diverge substantially across emissions scenarios. For some sectors, for example, vector-borne diseases, heat/cold stress, and agricultural production and undernutrition, there may be benefits to health in some areas, but the net impact is expected to be negative. Estimated impacts are also presented for the longer-term "era of climate options" (2080–2100), for global mean temperature increase of 4°C above preindustrial levels, which could potentially be avoided by vigorous mitigation efforts taken soon. For each timeframe, impact levels are estimated for the current state of adaptation and for a hypothetical highly adapted state, indicated by different colors.

11.8. Adaptation Limits Under High Levels of Warming

Most attempts to quantify health burdens associated with future climate change consider modest increases in global average temperature, typically less than 2°C. However, research published since AR4 raises doubt over whether it will be possible to limit global warming to 2°C above preindustrial temperatures (Rogelj et al., 2009; Anderson and Bows, 2011; PriceWaterhouseCoopers, 2012). It is therefore increasingly important to examine the likely health consequences of warming beyond 2°C, including extreme warming of 4°C to 6°C or higher. Predictions of this nature are limited by uncertainty about climatic as well as key, non-climatic determinants of health including the nature and degree of adaptation. Here, we instead focus primarily on physiological or ecological limits that constrain our ability to adapt and protect human health and wellbeing (Section 16.4.1).

It can be assumed that the increase in many important climate-related health impacts at increasingly higher levels of warming will be greater than simple linear increments; that is, that the health consequences of a 4°C temperature increase will be more than twice those of a +2°C world (see Figure 11-6). Nonlinear and threshold effects have been

observed in the mortality response to extreme heat (Anderson and Bell, 2011; McMichael, 2013a), agricultural crop yields, as key determinants of childhood nutrition and development (Schlenker and Roberts, 2009; Lobell et al., 2011a), and infectious diseases (Altizer et al., 2006), for example. These are also briefly elaborated here.

11.8.1. Physiological Limits to Human Heat Tolerance

In standard (or typical) conditions, core body temperatures will reach lethal levels under sustained periods of wet-bulb temperatures above about 35°C (Sherwood and Huber, 2010). Sherwood and Huber (2010) conclude that a global mean warming of roughly 7°C above current temperatures would create small land areas where metabolic heat dissipation would become impossible. An increase of 11°C to 12°C would enlarge these zones to encompass most of the areas occupied by today's human population. This analysis is likely a conservative estimate of an absolute limit to human heat tolerance because working conditions are hazardous at lower thresholds. The U.S. military, for example, suspends all physical training and strenuous exercise when the wet-bulb globe temperature (WBGT) exceeds 32°C (Willett and Sherwood, 2012) while international labor standards suggest the time acclimatized individuals spend doing low intensity labor such as office work be halved under such conditions (Kjellstrom et al., 2009a).[1] One estimate suggests global labor productivity will be reduced during the hottest months to 60% in 2100 and less than 40% in 2200 under the RCP8.5 scenario in which global mean temperatures rise 3.4°C by 2100 and 6.2°C by 2200 relative to 1861–1960 (Dunne et al., 2013). It is projected that tropical and mid-latitude regions including India, Northern Australia, and the southeastern USA will be particularly badly affected (Willett and Sherwood, 2012; Dunne et al., 2013).

11.8.2. Limits to Food Production and Human Nutrition

Agricultural crops and livestock similarly have physiological limitations in terms of thermal and water stress. For example, production of the staple crops maize, rice, wheat, and soybean is generally assumed to face an absolute temperature limit in the range of 40°C to 45°C (Teixeira et al., 2011), while key phenological stages such as sowing to emergence, grain-filling, and seed set have maximum temperature thresholds near or below 35°C (Yoshida et al., 1981; Porter and Gawith, 1999; Porter and Semenov, 2005). The existence of critical climatic thresholds and evidence of nonlinear responses of staple crop yields to temperature and rainfall (Brázdil et al., 2009; Schlenker and Roberts, 2009; Lobell et al., 2011b) thus suggest that there may be a threshold of global warming beyond which current agricultural practices can no longer support large human civilizations, and the impacts on malnourishment and undernutrition described in Section 11.6.1 will become much more severe. However, current models to estimate the human health consequences of climate-impaired food yields at higher global temperatures generally incorporate neither critical thresholds nor nonlinear response functions (Lloyd et al., 2011; Lake et al., 2012), reflecting uncertainties about exposure-response relations, future extreme events, the scale and feasibility of adaptation, and climatic thresholds for other influences such as infestations and plant diseases. Extrapolation from current models nevertheless suggests that the global risk to food security becomes very severe under an increase of 4°C to 6°C or higher in global mean temperature (*medium evidence*, *high agreement*) (Chapter 7, Executive Summary).

11.8.3. Thermal Tolerance of Disease Vectors

Substantial warming in higher-latitude regions will open up new terrain for some infectious diseases that are limited at present by low temperature boundaries, as already evidenced by the northward extensions in Canada and Scandinavia of tick populations, the vectors for Lyme disease and tick-borne encephalitis (Lindgren and Gustafson, 2001; Ogden et al., 2006). On the other hand, the emergence of new temperature regimes that exceed optimal conditions for vector and host species will reduce the potential for infectious disease transmission and, with high enough temperature rise, may eventually eliminate some infectious diseases that exist at present close to their upper tolerable temperature limits. For example, adults of two malaria-transmitting mosquito species are unable to survive temperatures much above 40°C in laboratory experiments (Lyons et al., 2012), although in the external world they may seek out tolerable microclimates. Reproduction of the malaria parasite within the mosquito is impaired at lesser raised temperatures (Paaijmans et al., 2009). Larval development of *Aedes albopictus*, an Asian mosquito vector of dengue and chikungunya, also does not occur at or above 40°C (Delatte et al., 2009).

11.8.4. Displacement and Migration Under Extreme Warming

Weather extremes and longer term environmental change including sea level rise lead to both more people displaced and increase in populations that are effectively trapped (Section 12.4.1.2). This trend is expected to be more pronounced under extreme levels of warming (Section 16.5). Gemenne (2011) argues that the most significant difference between the nature of human migration in response to 4°C of warming relative to 2°C would be to remove many people's ability to choose whether to stay or leave when confronted with environmental changes. Health studies of refugees, migrants, and people in resettlement schemes suggest that forced displacement, in turn, is likely to lead to more adverse health impacts than voluntary migration or planned resettlement (McMichael et al., 2012). The health risks associated with forced displacement include undernutrition; food- and water-borne illnesses; diseases related to overcrowding such as measles, meningitis, and acute respiratory infections; sexually transmitted diseases; increased maternal mortality; and mental health disorders (McMichael et al., 2012).

11.8.5. Reliance on Infrastructure

Under severe climate regimes, societies may be able to protect themselves by enclosing places for living and working, first for their most vulnerable

[1] WBGT is a heat index closely related to the wet-bulb temperature that also incorporates measures of radiant heat from the sun and evaporative cooling due to wind.

members: the young, old, ill, and manual laborers. This strategy will mean increased vulnerability to infrastructure failure and unreliable energy and water supplies. Electrical power outages have been linked to both accidental and disease-related deaths in temperate climates (Anderson and Bell, 2012), and failures in power supplies are more likely to occur during extreme weather events (Section 19.6.2.1). Large-scale reliance on air conditioning under a significantly hotter climate regime would therefore pose a serious health risk.

11.9. Co-Benefits

Essentially every human activity affects (and is affected by) climate and health status in some way, but not all are strongly linked to either and even fewer strongly to both. Here we focus on measures to mitigate the atmospheric concentration of warming climate-altering pollutants that also hold the potential to significantly benefit human health. These so-called co-benefits include health gains from strategies that are directed primarily at climate change, and mitigation of climate change from well-chosen policies for health advancement (Haines et al., 2007; Apsimon et al., 2009; Smith and Balakrishnan, 2009; UNEP, 2011; Shindell et al., 2012). The literature on health co-benefits associated with climate change mitigation strategies falls into several categories (Smith and Balakrishnan, 2009; Smith et al., 2009). These include:

- Reduce emissions of health-damaging pollutants, either primary or precursors to other pollutants in association with changes in energy production, energy efficiency, or control of landfills
- Increase access to reproductive health services
- Decrease meat consumption (especially from ruminants) and substitute low-carbon healthy alternatives
- Increase active transport particularly in urban areas
- Increase urban green space.

In addition, although not discussed here, there are potential health side effects of mitigation measures, such as geoengineering, biofuel expansion, and carbon taxes that are potentially deleterious for human health (Tilman et al., 2009; see Chapter 19). In Table 11-3, we summarize what is known about the main categories of co-benefits, but because of space limitation, we only provide additional detail for two of them below.

11.9.1. Reduction of Co-Pollutants

Most of the publications related to CAPs and health-damaging pollutants refer to fuel combustion and fall into three major categories: (1) improvement in energy efficiency will reduce emissions of CO_2 and health-damaging pollutants, providing these gains are not outpaced by increases in energy demand, and the energy is derived from combustion of fossil fuels or non-renewable biomass fuels, either directly or through the electric power system; (2) increases of combustion efficiency (decreasing emission of incomplete combustion products) will have both climate and health benefits, even if there is no change in energy efficiency and/or fuel itself is renewable, because a number of the products of incomplete combustion are climate altering and nearly all are damaging to health (Smith and Balakrishnan, 2009); and (3) increased use of non-combustion sources, such as wind, solar, tidal, wave, and geothermal energy, would reduce emissions of warming CAPs and health damaging air pollutants, providing benefits for climate and health (Jacobson et al., 2013).

Studies of the health co-benefits of reduction in air pollutants include sources that produce outdoor air pollution (Bell et al., 2008a) and household sources (Po et al., 2011). In many parts of the world, household fuels (poorly combusted biomass and coal) are responsible for a substantial percent of primary outdoor fine particle pollution as well, perhaps a quarter in India for example (Lim et al., 2012). In many parts of the world, household fuel (poorly combusted biomass and coal) is responsible for much fine particle outdoor air pollution and may contribute to long-range transport of hazardous air pollutants (Anenberg et al., 2013). This indicates that reductions in emissions from household sources will yield co-benefits through the outdoor pollution pathway.

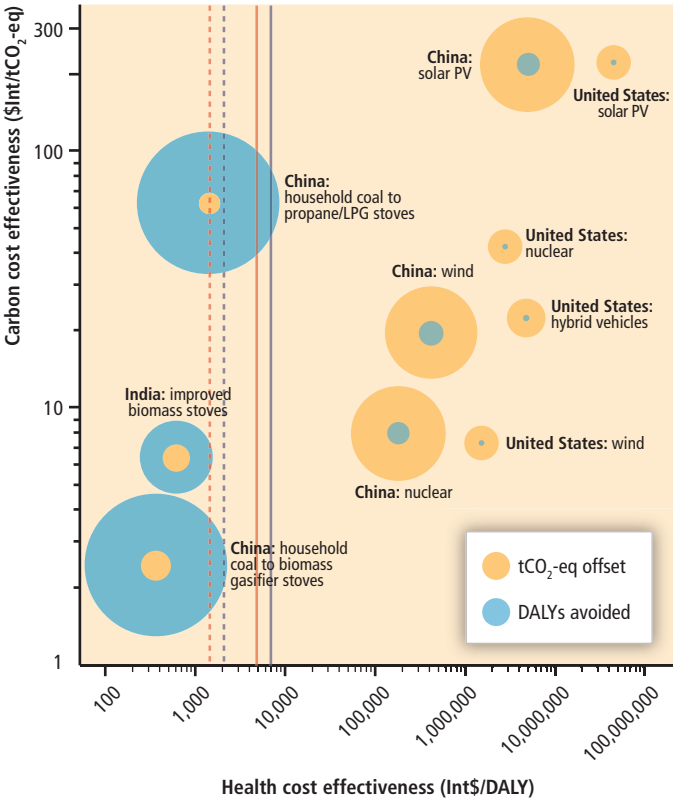

Figure 11-7 | Illustrative co-benefits comparison of the health and climate cost-effectiveness of selected household, transport, and power sector interventions (Smith and Haigler, 2008). Area of each circle denotes the total social benefit in international dollars (Int$) from the combined value of carbon offsets (valued at 10$/$tCO_2$-eq (tons of carbon dioxide equivalent)) and averted disability-adjusted life years (DALYs; $7450/DALY, which is representative of valuing each DALY at the average world gross domestic product (PPP) per capita in 2000). The vertical lines shows the range of the cut offs for cost-effective (solid lines) and very cost-effective (dashed lines) health interventions in India (red lines) and China (purple lines) using the WHO CHOICE (CHOosing Interventions that are Cost-Effective) criteria (WHO, 2003). This figure evaluates only a small subset of all co-benefits opportunities, and thus should not be considered either current or complete. It does illustrate, however, the kind of comparisons that can help distinguish and prioritize options. Note that even with the log-log scaling, there are big differences among them. For other figures comparing the climate and health benefits of co-benefits actions including those in food supply and urban design, see Haines et al. (2009). See the original reference for details of the calculations in this figure (Smith and Haigler, 2008).

Table 11-3 | Examples of recent (post-AR4) research studies on co-benefits of climate change mitigation and public health policies. For recent estimates of the global and regional burden of disease from the various risk factors involved, see Lim et al. (2012). (CAP = climate-altering pollutant.)

Co-benefit category	Benefits for health	Benefits for climate	References
Reduction of co-pollutants from household solid fuel combustion (see also WGIII AR5, Chapters 7 to 10)	Potentially reduce exposures that are associated with disease, chronic and acute respiratory illnesses, lung cancer, low birth weight and stillbirths, and possibly tuberculosis	Reduces CAP emissions associated with household solid fuel use including CO_2, CO, black carbon, and CH_4	Bell et al. (2008); Smith et al. (2008); Wilkinson et al. (2009); Lefohn et al. (2010); Venkataraman et al. (2010); World Health Organization Regional Office for Europe (2010); Po et al. (2011); Anenberg et al. (2012)
Reduction of greenhouse gases and associated co-pollutants from industrial sources, such as power plants and landfills, by more efficient generation or substitution of low carbon alternatives (Section 27.3.7.2)	Reductions in health-damaging co-pollutant emissions would decrease exposures to outdoor air pollution and could reduce risks of cardiovascular disease, chronic and acute respiratory illnesses, lung cancer, and preterm birth.	Reductions in emissions of CO_2, black carbon, CO, CH_4, and other CAPs	Bell et al. (2008); Apsimon et al. (2009); Jacobson (2009); Puppim de Oliveira et al. (2009); Smith et al. (2009); Tollefsen et al. (2009); Dennekamp et al. (2010); Jacobson (2010); Nemet et al. (2010); Rive and Aunan (2010); Shonkoff et al. (2011); Shindell et al. (2012); West et al. (2012); West et al. (2013)
Energy efficiency. Actual energy reduction may sometimes be less than anticipated because part of the efficiency benefit is taken as more service.	Reductions in fuel demand potentially can reduce emissions of CAPs associated with fuel combustion and subsequent exposures to pollutants that are known to be health damaging.	Reductions in emission of CAPs due to decreases in fuel consumption	Markandya et al. (2009); Wilkinson et al. (2009)
Increases in active travel and reductions in pollution due to modifications to the built environment, including better access to public transport and higher density of urban settlements (see also Sections 24.4, 24.5, 24.6, 24.7, 26.8)	Increased physical activity; reduced obesity; reduced non-communicable disease burden, health service costs averted; improved mental health; reduced exposure to air pollution; increased local access to essential services, including food stores; enhanced safety	Reductions of CAP emissions associated with vehicle transport; replacing existing vehicles with lower emission vehicles could reduce air pollution.	Babey et al. (2007); Reed and Ainsworth (2007); Kaczynski and Henderson (2008); Casagrande et al. (2009); Jarrett et al. (2009); Rundle et al. (2009); Woodcock et al. (2009); Durand et al. (2011); Grabow et al. (2011); McCormack and Shiell (2011); Jensen et al. (2013); Woodcock et al. (2013)
Healthy low greenhouse gas emission diets, which can have beneficial effects on a range of health outcomes (see also Table 11.3)	Reduced dietary saturated fat in some populations (particularly from ruminants) and replacement by plant sources associated with decreased risk of (ischemic) heart disease, stroke, colorectal cancer (processed meat consumption). Increased fruit and vegetable consumption can reduce risk of chronic diseases. Reduced CH_4 emissions due to a decreased demand for ruminant meat products would reduce tropospheric ozone.	Reductions in CO_2 and CH_4 emissions from energy-intensive livestock systems	McMichael et al. (2007); Friel et al. (2009); Sinha et al. (2009); Smith and Balakrishnan (2009); Jakszyn et al. (2011); Hooper et al. (2012); Pan et al. (2012); Xu et al. (2012)
Greater access to reproductive health services	Lower child and maternal mortality from increased birth intervals and shifts in maternal age	Potentially slower growth of energy consumption and related CAP emissions; less impact on land use change, etc.	Tsui et al. (2007); Gribble et al. (2009); Prata (2009); O'Neill et al. (2010); Diamond-Smith and Potts (2011); Potts and Henderson (2012); Kozuki et al. (2013)
Increases in urban green space (Table 25-5)	Reduced temperatures and heat island effects; reduced noise; enhanced safety; psychological benefits; better self-perceived health status	Reduces atmospheric CO_2 via carbon sequestration in plant tissue and soil	Mitchell and Popham (2007); Babey et al. (2008); Maas et al. (2009); van den Berg et al. (2010); van Dillen et al. (2011)
Carbon sequestration in forest plantations, reducing emissions from deforestation and degradation, and carbon offset sales (see Chapter 13 and Section 15.3.4; see also Sections 20.4.1 and 26.8.4.3)	Poverty alleviation and livelihood/job generation through sale of Clean Development Mechanism and voluntary market credits. Ameliorate declines in production or competitiveness in rural communities	Reduces emissions of CAPs and promotes carbon sequestration through reducing emissions from deforestation and degradation	Holmes (2010); Ezzine-de-Blas et al. (2011)

If interventions result in reductions in coal combustion, there are a range of other potential health benefits beyond reduction of particulate air pollution emissions, including reducing other types of health-damaging emissions and the human impacts from coal mining (Lockwood, 2012; Smith et al., 2013).

Another category of air pollution co-benefits comes from controls on methane emissions that both reduce radiative forcing and potentially reduce human exposures to ambient ozone, for which methane is a precursor.

11.9.1.1. Outdoor Sources

Primary co-pollutants, such as particulate matter (PM) and carbon monoxide (CO) are those released at the point of combustion, while secondary co-pollutants, such as tropospheric ozone and sulfate particles, are formed downwind from the combustion source via atmospheric chemical interactions (Jerrett et al., 2009) and can be transported long distances.

The burden of disease from outdoor exposures in a country may often be greater in populations with low socioeconomic status, both because of living in areas with higher exposures and because these populations often have worse health and are subjected to multiple additional negative environmental and social exposures (Morello-Frosch et al., 2011).

11.9.1.2. Household Sources

Globally, the largest exposures from the pollutants from poor fuel combustion occur in the poorest populations. This is because household use of biomass for cooking is distributed nearly inversely with income. Essentially, no poor family can afford gas or electricity for cooking and very few families who can afford to do so, do not. Thus, the approximate 41% of all world households using solid fuels for cooking are all among

the poor in developing countries (Bonjour et al., 2013). Although biomass makes up the bulk of this fuel and creates substantial health impacts from products of incomplete combustion when burned in simple stoves (Lim et al., 2012), probably the greatest health and largest climate impacts per household result from use of coal, which can also be contaminated with sulfur and a range of toxic elements as well (Edwards et al., 2004; Zhang and Smith, 2007). Successfully accelerating the reduction of impacts from these fuels, however, has not been found to be easily accomplished with biomass/coal stove programs implemented to date and may require moving to clean fuels (Bruce et al., 2013). The climate benefits from improving household biomass fuel combustion come in part from potential reduction of net warming by reducing emissions of aerosols (including black carbon), but more confidently from reduction of CH_4 and other CAPs that are produced by incomplete combustion, as well as reductions in net CO_2 emissions if interventions are applied in areas relying on non-renewably harvested wood fuel (WGI AR5 Section 8.5.3).

11.9.1.3. Primary Co-Pollutants

Outdoor exposure to PM, especially to particles with diameters less than 2.5 µm ($PM_{2.5}$), contributes significantly to ill health including cardio- and cerebrovascular disease, adult chronic and child acute respiratory illnesses, lung cancer, and possibly other diseases. The Comparative Risk Assessment (CRA) for outdoor air pollution done as part of the Global Burden of Disease (GBD) 2010 Project found approximately 3.2 million premature deaths globally from ambient particle pollution or about 3% of the global burden of disease (Lim et al., 2012). Importantly, reductions in ambient PM concentrations have also been shown to decrease morbidity and premature mortality (Boldo et al., 2010). A significant portion of ambient particle pollution derives from fuel combustion, perhaps 80% globally (GEA, 2012).

Because of higher exposures, an additional set of diseases has also been associated with combustion products in households burning biomass and/or coal for cooking and heating. Thus, in addition to the diseases noted above, cataracts, low birth weight, and stillbirth have been associated strongly with exposures to incomplete combustion products, such as PM and CO. CO has impacts on unborn children *in utero* through exposures to their pregnant mothers (WHO Regional Office for Europe, 2010). There is also growing evidence of exacerbation of tuberculosis (Pokhrel et al., 2010) in adults and cognitive effects in children (Dix-Cooper et al., 2012). The CRA of the GBD-2010 found 3.5 million premature deaths annually from household air pollution derived from cooking fuels or 4.4% of the global burden of disease (Lim et al., 2012). Importantly, there are also studies showing health benefits of household interventions, for child pneumonia (Smith et al., 2011), blood pressure (McCracken et al., 2007; Baumgartner et al., 2011) , lung cancer (Lan et al., 2002), and chronic obstructive pulmonary disease (Chapman et al., 2005). Another half a million premature deaths are attributed to household cookfuel's contribution to outdoor air pollution, making a total of about 4 million in 2010 or 4.9% of the global burden of disease (Lim et al., 2012).

Black carbon (BC), a primary product of incomplete combustion, is both a strong CAP and health-damaging (IPCC, 2007; Ramanathan and Carmichael, 2008; Bond et al., 2013). A systematic review, meta-analysis, and the largest cohort study to date of the health effects of BC found that there were probably stronger effects on mortality from exposure to BC than for undifferentiated fine particles ($PM_{2.5}$) (Smith et al., 2009). Reviews have concluded that abatement of particle emissions including BC represents an opportunity to achieve both climate mitigation and health benefits (UNEP, 2011; Shindell et al., 2012). WGI AR5 (Box TS-6), however, concluded that the net impact of BC emissions reductions overall is not certain as to sign, i.e., whether net warming or cooling. Nevertheless, there would be co-benefits in circumstances where BC is emitted without many other cooling aerosols, as with diesel and kerosene combustion (Lam et al., 2012).

Other examples of climate forcing, health-damaging co-pollutants of CO_2 from fuel use are carbon monoxide, non-methane hydrocarbons, and sulfur and nitrogen oxides. Each co-pollutant poses risks as well as being climate altering in different ways. See WGI for more on climate potential and WHO reviews of health impacts (WHO, 2006; WHO Regional Office for Europe, 2010).

11.9.1.4. Secondary Co-Pollutants

In addition to being a strong GHG, methane is also a significant precursor to regional anthropogenic tropospheric ozone production, which itself is both a GHG and damaging to health, crops, and ecosystems (WGI AR5 TS.5.4.8). Thus, reductions in CH_4 could lead to reductions in ambient tropospheric ozone concentrations, which in turn could result in reductions in population morbidity and premature mortality and climate forcing.

One study found that a reduction of global anthropogenic CH_4 emissions by 20% beginning in 2010 could decrease the average daily maximum 8-hour surface ozone by 1 ppb by volume, globally—sufficient to prevent 30,000 premature all-cause mortalities globally in 2030, and 370,000 between 2010 and 2030 (West et al., 2012). CH_4 emissions are generally accepted as the primary anthropogenic source of tropospheric ozone concentrations above other human-caused emissions of ozone precursors (West et al., 2007b), and thus the indirect health co-benefits of CH_4 reductions are epidemiologically significant. On the other hand, work done for the GBD-2010 estimated 150,000 premature deaths from all ozone exposures globally in 2010, indicating a more conservative interpretation of the evidence for mortality from ozone (Lim et al., 2012).

In an analysis of ozone trends from 1998–2008 in the USA, Lefohn et al. (2010) found that 1-hour and 8-hour ambient ozone averages have either decreased or failed to increase due to successful regulations of ozone precursors, predominantly NO_x and CH_4. This is consistent with the EPA (2013) conclusion that in the USA, for the period 1980–2012, emissions of nitrogen oxides and volatile organic compounds fell by 59% and 57%, respectively (Lefohn et al., 2010; EPA, 2013). These results point to the effectiveness of reducing ambient ozone concentrations through regulatory tools that reduce the emissions of ozone precursors, some of which, like CH_4, are GHGs.

Not every CAP emitted from fuel combustion is warming. The most prominent example is sulfur dioxide emitted from fossil fuel combustion, which changes to particle sulfate in the atmosphere. Although health

damaging, sulfate particles have a cooling effect on global radiative forcing. Thus, reduction of sulfur emissions, which is important for health protection, does not qualify as a co-benefit activity because it actually acts to unmask more of the warming effect of other CAP emissions (Smith et al., 2009).

11.9.1.5. Case Studies of Co-Benefits of Air Pollution Reductions

A recent United Nations Environment Programme (UNEP)- and World Meteorological Organization (WMO)-led study of BC and tropospheric ozone found that, if all of 400 proposed BC and CH_4 mitigation measures were implemented on a global scale, the estimated benefits to health would come predominately from reducing $PM_{2.5}$ (0.7 to 4.6 million avoided premature deaths; 5.3 to 37.4 million avoided years of life lost) compared to tropospheric ozone (0.04 to 0.52 million avoided premature deaths; 0.35 to 4.7 million avoided years of life lost) based on 2030 population figures (UNEP, 2011). About 98% of the avoided deaths would come from reducing $PM_{2.5}$, with 80% of the estimated health benefits occurring in Asia (Anenberg et al., 2012). Another study of the reduction of PM and ozone exposures due to CAPs emissions controls and including climate change feedback showed potential reductions of 1.3 million premature deaths by 2050 with avoided costs of premature mortality many times those of the estimated cost of abatement (West et al., 2013).

A study of the benefits of a hypothetical 10-year program to introduce advanced combustion cookstoves in India found that in addition to reducing premature mortality by about 2 million and DALYs by 55 million over that period, there would be a reduction of 0.5 to 1.0 billion tons CO2-eq (Wilkinson et al., 2009). Another study of India found a potential to reduce 570,000 premature deaths a year, one-third of national BC emissions, and 4% of all national GHG emissions by hypothetical substitution of clean household fuel technologies (Venkataraman et al., 2010).

In their estimation of effects of hypothetical physical and behavioral modifications in UK housing, Wilkinson and colleagues (Wilkinson et al., 2009) found that the magnitude and direction of implications for health depended heavily on the details of the intervention. However, the interventions were found to be generally positive for health. In a strategy of housing modification that included insulation, ventilation control, and fuel switching, along with behavioral changes, it was estimated that 850 fewer DALYs, and a savings of 0.6 megatonnes of CO_2 per million population in 1 year, could be achieved. These calculations were made by comparing the health of the 2010 population with and without the specified physical and behavioral modifications (Wilkinson et al., 2009).

Markandya et al. (2009) assessed the changes in emissions of $PM_{2.5}$ and subsequent effects on population health that could result from climate change mitigation measures aimed to reduce GHG emissions by 50% by 2050 (compared with 1990 emissions) from the electricity generation sector in the EU, China, and India. In all three regions, changes in modes of production of electricity to reduce CO_2 emissions were found to reduce $PM_{2.5}$ and associated mortality. The greatest effect was found in India and the smallest in the EU. The analysis also found that if the health benefits were valued similarly to the approach used by the EU for air pollution, they offset the cost of GHG emission reductions, especially in the Indian context where emissions are high but costs of implementing the measures are low (Markandya et al., 2009).

11.9.2. Access to Reproductive Health Services

Population growth influences the consumption of resources and emissions of CAPs (Cohen, 2010). Although population growth rates and total population size do not alone determine emissions, population size is an important factor. One study showed that CO_2 emissions could be lower by 30% by 2100 if access to contraception was provided to those women expressing a need for it (O'Neill et al., 2012). Providing the unmet need for these services in areas such as the Sahel region of Africa that has both high fertility and high vulnerability to climate change can potentially significantly reduce human suffering as climate change proceeds (Potts and Henderson, 2012).

This is important not only in poor countries, however, but also some rich ones like the USA, where there is unmet need for reproductive health services as well as high CO_2 emissions per capita (Cohen, 2010). Also, because of income rise in developing countries and concurrent reduction of greenhouse emissions in developed countries, a convergence in emissions per capita is expected in most scenarios by 2100 (WGI AR5 TS.5.2). Slowing population growth through lowering fertility, as might be achieved by increasing access to family planning, has been associated with improved maternal and child health—the co-benefit—in two main ways: increased birth spacing and reducing births by very young and old mothers.

11.9.2.1. Birth and Pregnancy Intervals

Current evidence supports, with *medium confidence*, that short birth intervals (defined as birth intervals ≤24 months and inter-pregnancy intervals <6 months) are associated with increased risks of uterine rupture and bleeding (placental abruption and placenta previa) (Bujold et al., 2002; Conde-Agudelo et al., 2007).

There is also a correlation between short birth interval and elevated risk of low birth weight (Zhu, 2005). Zhu (2005) found, in a review of three studies performed in the USA, that the smallest risk of low birth weight was found with inter-pregnancy spacing between 18 and 23 months. Another review of five cohort studies found that a birth interval shorter than 18 months was significantly associated with increased low birth weight, preterm birth, and infant mortality after controlling for confounding factors (Kozuki et al., 2013).

Although an ecological analysis, a review across 17 countries shows a strikingly coherent picture of the relationship between birth spacing and reductions in child, infant, and neonatal mortality, with risk of child undernutrition and mortality both increasing with shorter birth intervals (Rutstein, 2005). One study estimated that shifting birth spacing from current patterns in the world to a minimum of 24 months would reduce by 20% (approximately 2 million) the current excess child mortality in the world (Rutstein, 2005; Gribble et al., 2009).

11.9.2.2. Maternal Age at Birth

Risk of death during delivery is highest in very young and very old mothers, and these are also the age groups that most often want to control their fertility (Engelman, 2010). Women who begin child bearing under the age of 20 years are at an increased risk of developing pregnancy complications such as cephalopelvic disproportion, obstructed labor, preterm delivery, toxemia, bleeding, and maternal death (Tsui et al., 2007). In addition, children born to women younger than the age of 20 are at increased risk of fetal growth retardation and low birth weight, both of which can lead to long-term physical and mental developmental problems (Tsui et al., 2007). Childbearing at later ages (>35 years) is associated with increased risk of miscarriage and other adverse health outcomes (Cleary-Goldman et al., 2005; Ujah et al., 2005).

Providing access to family planning saves women's lives by reducing the total number of births and, in particular, through the reduction of births in high-risk groups (Prata, 2009) while simultaneously reducing total fertility and subsequent CAP emissions. Studies have found that when women have access to family planning, it is the highest risk age groups (youngest and oldest women) who reduce their fertility the most. In other words, family planning has a differential impact on maternal mortality reduction through reducing births in the highest risk groups (Diamond-Smith and Potts, 2011).

11.10. Key Uncertainties and Knowledge Gaps

There is evidence that poverty alleviation, public health interventions such as provision of water and sanitation, and early warning and response systems for disasters and epidemics will help to protect health from climate risks. The key uncertainty is the extent to which society will strengthen these services, including taking into account the risks posed by climate change. With a strong response, climate change health effects are expected to be relatively small in the next few decades, but otherwise climate-attributable cases of disease and injury will steadily increase.

Since AR4, national governments, through the World Health Assembly, have specifically called for increased research on (1) the scale and nature of health risks from climate change; (2) effectiveness of interventions to protect health; (3) health implications of adaptation and mitigation decisions taken in other sectors, (4) improvement in decision support systems and surveillance, and (5) estimation of resource requirements. A recent scoping review identified quantitative peer-reviewed studies across all of these areas, with the exception of studies on the effectiveness or cost-effectiveness of targeted adaptation measures (Hosking and Campbell-Lendrum, 2012). There are also comparatively few studies of vulnerability in low- and middle-income populations, or of more complex disease pathways, such as the effect of more extreme weather on water and sanitation provision and diarrhea rates, on zoonotic diseases, or mental health. Studies of health co-benefits of climate change mitigation policies also remain rare compared to the size of the potential health gains. Potential negative side effects also need to be addressed, for example those arising from biofuel policies that compete with food production.

Relevant research for health protection in the near term is therefore likely to come from cross-disciplinary studies, including public health decision makers, in the following areas: improved vulnerability and adaptation assessments that focus on particularly vulnerable populations and encompass complex causal pathways; quantitative estimation of the effectiveness of health adaptation measures; surveillance, monitoring, and observational systems that link climate, health, and economic impact data and provide a basis for early warning systems as well as development of future scenarios; and assessment of the health co-benefits of alternative climate mitigation policies.

In the longer term, research will need to make the best use of traditional epidemiologic methods, while also taking into account the specific characteristics of climate change. These include the long-term and uncertain nature of the exposure and effects on multiple physical and biotic systems, with the potential for diverse and widespread effects, including high-impact events. There are low-probability, but plausible, scenarios for extreme climate regimes before the end of the century. Although difficult, it is important to develop robust methods to investigate the health implications of conditions that may apply in 2100, as decisions today about mitigation will determine their likelihood. Given the increase globally in life expectancies, many babies born this decade will be alive at the end of the century, and will be personally affected by the climate that is in place in 2100.

Frequently Asked Questions

FAQ 11.1 | How does climate change affect human health?

Climate change affects health in three ways: (1) directly, such as the mortality and morbidity (including "heat exhaustion") due to extreme heat events, floods, and other extreme weather events in which climate change may play a role; (2) indirect impacts from environmental and ecosystem changes, such as shifts in patterns of disease-carrying mosquitoes and ticks, or increases in waterborne diseases due to warmer conditions and increased precipitation and runoff; and (3) indirect impacts mediated through societal systems, such as undernutrition and mental illness from altered agricultural production and food insecurity, stress, and violent conflict caused by population displacement; economic losses due to widespread "heat exhaustion" impacts on the workforce; or other environmental stressors, and damage to health care systems by extreme weather events.

Frequently Asked Questions

FAQ 11.2 | Will climate change have benefits for health?

Yes. For example some populations in temperate areas may be at less risk from extreme cold, and may benefit from greater agricultural productivity, at least for moderate degrees of climate change. Some areas currently prone to flooding may become less so. However, the overall impact for nearly all populations and for the world as a whole is expected to be more negative than positive, increasingly so as climate change progresses. In addition, the latitude range in the world that may benefit from less cold (e.g., the far north of the Northern Hemisphere) has fewer inhabitants compared with the equatorial latitudes where the burden will be greatest.

Frequently Asked Questions

FAQ 11.3 | Who is most affected by climate change?

While the direct health effects of extreme weather events receive great attention, climate change mainly harms human health by exacerbating existing disease burdens and negative impacts on daily life among those with the weakest health protection systems, and with the least capacity to adapt. Thus, most assessments indicate that poor and disenfranchised groups will bear the most risk and, globally, the greatest burden will fall on poor countries, particularly on poor children, who are most affected today by such climate-related diseases as malaria, undernutrition, and diarrhea. However, the diverse and global effects of climate change mean that higher income populations may also be affected by extreme events, emerging risks, and the spread of impacts from more vulnerable populations.

Frequently Asked Questions

FAQ 11.4 | What is the most important adaptation strategy to reduce the health impacts of climate change?

In the immediate future, accelerating public health and medical interventions to reduce the present burden of disease, particularly diseases in poor countries related to climatic conditions, is the single most important step that can be taken to reduce the health impacts of climate change. Priority interventions include improved management of the environmental determinants of health (such as provision of water and sanitation), infectious disease surveillance, and strengthening the resilience of health systems to extreme weather events. Alleviation of poverty is also a necessary condition for successful adaptation.

There are limits to health adaptation, however. For example, the higher-end projections of warming indicate that before the end of the 21st century, parts of the world may experience temperatures that exceed physiological limits during periods of the year, making it impossible to work or carry out other physical activity outside.

Frequently Asked Questions

FAQ 11.5 | What are health "co-benefits" of climate change mitigation measures?

Many mitigation measures that reduce emissions of those climate-altering pollutants (CAPs) that warm the planet have important direct health benefits in addition to reducing the risk of climate change. This relationship is called "co-benefits." For example, increasing combustion efficiency in households cooking with biomass or coal could have climate benefits by reducing CAPs and at the same time bring major health benefits among poor populations. Energy efficiency and reducing reliance on coal for electricity generation not only reduces emissions of greenhouse gases, but also reduces emissions of fine particles that cause many premature deaths worldwide as well as reducing other health impacts from the coal fuel cycle. Programs that encourage "active transport" (walking and cycling) in place of travel by motor vehicle reduce both CAP emissions and offer direct health benefits. A major share of greenhouse gas emissions from the food and agriculture sector arises from cows, goats, and sheep—ruminants that create the greenhouse gas methane as part of their digestive process. Reducing consumption of meat and dairy products from these animals may reduce ischemic heart disease (assuming replacement with plant-based polyunsaturates) and some types of cancer. Programs to provide access to reproductive health services for all women will not only lead to slower population growth and its associated energy demands, but also will reduce the numbers of child and maternal deaths.

References

Abuaku, B.K., J. Zhou, X. Li, S. Li, A. Liu, T. Yang, and H. Tan, 2009: Morbidity and mortality among populations suffering floods in Hunan, China: the role of socioeconomic status. *Journal of Flood Risk Management*, **2(3)**, 222-228.

Acosta-Michlik, L., U. Kelkar, and U. Sharma, 2008: A critical overview: local evidence on vulnerabilities and adaptations to global environmental change in developing countries. *Global Environmental Change*, **18(4)**, 539-542.

Ahern, M.J., R.S. Kovats, P. Wilkinson, R. Few, and F. Matthies, 2005: Global health impacts of floods: epidemiological evidence. *Epidemiologic Reviews*, **27**, 36-45.

Albrecht, G., G.M. Sartore, L. Connor, N. Higginbotham, S. Freeman, B. Kelly, H. Stain, A. Tonna, and G. Pollard, 2007: Solastalgia: the distress caused by environmental change. *Australasian Psychiatry*, **15 (Suppl. 1)**, S95-S98.

Alderman, H., 2010: Safety nets can help address the risks to nutrition from increasing climate variability. *The Journal of Nutrition*, **140(Suppl. 1)**, 148S-152S.

Alexander, K.A., M. Carzolio, D. Goodin, and E. Vance, 2013: Climate change is likely to worsen the public health threat of diarrheal disease in Botswana. *International Journal of Environmental Research and Public Health*, **10(4)**, 1202-1230.

Alonso, D., M.J. Bouma, and M. Pascual, 2011: Epidemic malaria and warmer temperatures in recent decades in an East African highland. *Proceedings of the Royal Society B*, **278(1712)**, 1661-1669.

Alston, M. and J. Kent, 2008: The Big Dry: the link between rural masculinities and poor health outcomes for farming men. *Journal of Sociology*, **44(2)**, 133-147.

Altizer, S., A. Dobson, P. Hosseini, P. Hudson, M. Pascual, and P. Rohani, 2006: Seasonality and the dynamics of infectious diseases. *Ecology Letters*, **9(4)**, 467-484.

Analitis, A., I. Georgiadis, and K. Katsouyanni, 2012: Forest fires are associated with elevated mortality in a dense urban setting. *Occupational Environmental Medicine*, **69(3)**, 158-162.

Anderson, G.B. and M.L. Bell, 2011: Heat waves in the United States: mortality risk during heat waves and effect modification by heat wave characteristics in 43 U.S. communities. *Environmental Health Perspectives*, **119(2)**, 210-218.

Anderson, G.B. and M.L. Bell, 2012: Lights out: impact of the August 2003 power outage on mortality in New York, NY. *Epidemiology*, **23(2)**, 189-193.

Anderson, K. and A. Bows, 2011: Beyond 'dangerous' climate change: emission scenarios for a new world. *Philosophical Transactions of the Royal Society A*, **369(1934)**, 20-44.

Anderson, M., C. Carmichael, V. Murray, A. Dengel, and M. Swainson, 2012: Defining indoor heat thresholds for health in the UK. *Perspectives in Public Health*, **133(3)**, 158-164.

Andreassen, A., S. Jore, P. Cuber, S. Dudman, T. Tengs, K. Isaksen, H. Hygen, H. Viljugrein, G. Anestad, P. Ottesen, and K. Vainio, 2012: Prevalence of tick borne encephalitis virus in tick nymphs in relation to climatic factors on the southern coast of Norway. *Parasites & Vectors*, August 2012, **5**, 177, doi:10.1186/1756-3305-5-177.

Andriopoulos, P., A. Economopoulou, and G. Spanakos, 2013: A local outbreak of autochthonous Plasmodium vivax malaria in Laconia, Greece – a re-emerging infection in the southern borders of Europe? *International Journal of Infectious Disease*, **17(2)**, e125-e128.

Anenberg, S.C., J. Schwartz, D. Shindell, M. Amann, G. Faluvegi, Z. Klimont, G. Janssens-Maenhout, L. Pozzoli, R. van Dingenen, E. Vignati, L. Emberson, N.Z. Muller, J.J. West, M. Williams, V. Demkine, W.K. Hicks, J. Kuylenstierna, F. Raes, and V. Ramanathan, 2012: Global air quality and health co-benefits of mitigating near-term climate change through methane and black carbon emission controls. *Environmental Health Perspectives*, **120(6)**, 831-839.

Anenberg, S.C., K. Balakrishnan, J. Jetter, O. Masera, S. Mehta, J. Moss, and V. Ramanathan, 2013: Cleaner cooking solutions to achieve health, climate, and economic cobenefits. *Environmental Science & Technology*, **47(9)**, 3944-3952.

Angelini, P., P. Macini, A.C. Finarelli, C. Pol, C. Venturelli, R. Bellini, and M. Dottori, 2008: Chikungunya epidemic outbreak in Emilia-Romagna (Italy) during summer 2007. *Parassitologia*, **50(1-2)**, 97-98.

Anyamba, A., K.J. Linthicum, and J.L. Small, 2012: Climate teleconnections and recent patterns of human and animal disease outbreaks. *PLoS Neglected Tropical Diseases*, **6(1)**, e1465, doi:10.1371/journal.pntd.0001465.

Apsimon, H., M. Amann, S. Astrom, and T. Oxley, 2009: Synergies in addressing air quality and climate change. *Climate Policy*, **9(6)**, 669-680.

Ari, T.B., A. Gershunov, R. Tristan, B. Cazelles, K. Gage, and N.C. Stenseth, 2010: Interannual variability of human plague occurrence in the western United States explained by tropical and North Pacific Ocean climate variability. *The American Journal of Tropical Medicine and Hygiene*, **83(3)**, 624-632.

Astrom, C., J. Rocklov, S. Hales, A. Beguin, V. Louis, and R. Sauerborn, 2012: Potential distribution of dengue fever under scenarios of climate change and economic development. *Ecohealth*, **9(4)**, 448-454.

Atchison, C., M. Iturriza-Gomara, C. Tam, and B. Lopman, 2010: Spatiotemporal dynamics of rotavirus disease in Europe: can climate or demographic variability explain the patterns observed. *The Pediatric Infectious Disease Journal*, **29(6)**, 566-568.

Auffhammer, M., 2011: Agriculture: weather dilemma for African maize. *Nature Climate Change*, **1**, 27-28.

Babey, S.H., T.A. Hastert, and E.R. Brown, 2007: *Teens Living in Disadvantaged Neighborhoods Lack Access to Parks and Get Less Physical Activity*. Policy Brief, Center for Health Policy Research, University of California, Los Angeles (UCLA), Los Angeles, CA, USA, 6 pp.

Babey, S.H., T.A. Hastert, H. Yu, and E.R. Brown, 2008: Physical activity among adolescents. When do parks matter? *American Journal of Preventive Medicine*, **34(4)**, 345-348.

Baccini, M., T. Kosatsky, A. Analitis, H.R. Anderson, M. D'Ovidio, B. Menne, P. Michelozzi, A. Biggeri, and P.C. Grp, 2011: Impact of heat on mortality in 15 European cities: attributable deaths under different weather scenarios. *Journal of Epidemiology and Community Health*, **65(1)**, 64-70.

Bai, L., L.C. Morton, and Q. Liu, 2013: Climate change and mosquito-borne diseases in China: a review. *Globalization and Health*, **9(1)**, 10, doi:10.1186/1744-8603-9-10.

Bandyopadhyay, S., S. Kanji, and L. Wang, 2012: The impact of rainfall and temperature variation on diarrheal prevalence in sub-Saharan Africa. *Applied Geography*, **33**, 63-72.

Bangs, M.J., R.P. Larasati, A.L. Corwin, and S. Wuryadi, 2006: Climatic factors associated with epidemic dengue in Palembang, Indonesia: implications of short-term meteorological events on virus transmission. *Southeast Asian Journal of Tropical Medicine and Public Health*, **37(6)**, 1103-1116.

Bassil, K. and D. Cole, 2010: Effectiveness of public health interventions in reducing morbidity and mortality during heat episodes: a structured review. *International Journal of Environmental Research and Public Health*, **7(3)**, 991-1001.

Basu, R. and B.D. Ostro, 2008: A multicounty analysis identifying the populations vulnerable to mortality associated with high ambient temperature in California. *American Journal of Epidemiology*, **168(6)**, 632-637.

Battisti, D.S. and R.L. Naylor, 2009: Historical warnings of future food insecurity with unprecedented seasonal heat. *Science*, **323(5911)**, 240-244.

Baumgartner, J., J.J. Schauer, M. Ezzati, L. Lu, C. Cheng, J.A. Patz, and L.E. Bautista, 2011: Indoor air pollution and blood pressure in adult women living in rural China. *Environmental Health Perspectives*, **119(10)**, 1390-1395.

Beaglehole, R. and R. Bonita, 2008: Global public health: a scorecard. *Lancet*, **372(9654)**, 1988-1996.

Beebe, N.W., R.D. Cooper, P. Mottram, and A.W. Sweeney, 2009: Australia's dengue risk driven by human adaptation to climate change. *PLoS Neglected Tropical Diseases*, **3(5)**, e429, doi:10.1371/journal.pntd.0000429.

Beggs, P.J., 2010: Adaptation to impacts of climate change on aeroallergens and allergic respiratory diseases. *International Journal of Environmental Research and Public Health*, **7(8)**, 3006-3021.

Béguin, A., S. Hales, J. Rocklöv, C. Åström, V.R. Louis, and R. Sauerborn, 2011: The opposing effects of climate change and socio-economic development on the global distribution of malaria. *Global Environmental Change*, **21(4)**, 1209-1214.

Bélanger, M., K. Gray-Donald, J. O'Loughlin, G. Paradis, and J. Hanley, 2009: Influence of weather conditions and season on physical activity in adolescents. *Annals of Epidemiology*, **19(3)**, 180-6, doi: 10.1016/j.annepidem.2008.12.008.

Bell, M.L., R.D. Peng, and F. Dominici, 2006: The exposure-response curve for ozone and risk of mortality and the adequacy of current ozone regulations. *Environmental Health Perspectives*, **114(4)**, 532-536.

Bell, M.L., R. Goldberg, C. Hogrefe, P. Kinney, K. Knowlton, B. Lynn, J. Rosenthal, C. Rosenzweig, and J. Patz, 2007: Climate change, ambient ozone, and health in 50 US cities. *Climatic Change*, **82(1)**, 61-76.

Bell, M.L., D.L. Davis, L.A. Cifuentes, A.J. Krupnick, R.D. Morgenstern, and G.D. Thurston, 2008a: Ancillary human health benefits of improved air quality resulting from climate change mitigation. *Environmental Health*, **7**, 41, doi:10.1186/1476-069X-7-41.

Bell, M.L., M.S. O'Neill, N. Ranjit, V.H. Borja-Aburto, L.A. Cifuentes, and N.C. Gouveia, 2008b: Vulnerability to heat-related mortality in Latin America: a case-crossover study in Sao Paulo, Brazil, Santiago, Chile and Mexico City, Mexico. *International Journal of Epidemiology*, **37(4)**, 796-804.

Bennet, L., A. Halling, and J. Berglund, 2006: Increased incidence of Lyme borreliosis in southern Sweden following mild winters and during warm, humid summers. *European Journal of Clinical Microbiology & Infectious Diseases*, **25(7)**, 426-432.

Bennett, C.M. and A.J. McMichael, 2010: Non-heat related impacts of climate change on working populations. *Global Health Action*, **3**, 5460, doi:10.3402/gha.v3i0.5640.

Bennett, C.M., K.G. Dear, and A. McMichael, 2013: Shifts in the seasonal distribution of deaths in Australia, 1968-2007. *International Journal of Biometeorology*, **(April)**, doi:10.1007/s00484-013-0663-x.

Berry, H.L., 2007: "Crowded suburbs" and "killer cities": a brief review of the relationship between the urban environment and mental health. *New South Wales Public Health Bulletin*, **18(11-12)**, 222-227.

Berry, H.L., K. Bowen, and T. Kjellstrom, 2010: Climate change and mental health: a causal pathways framework. *International Journal of Public Health*, **55(2)**, 123-132.

Bhatt, S., P.W. Gething, O.J. Brady, J.P. Messina, A.W. Farlow, C.L. Moyes, J.M. Drake, J.S. Brownstein, A.G. Hoen, O. Sankoh, M.F. Myers, D.B. George, T. Jaenisch, G.R.W. Wint, C.P. Simmons, T.W. Scott, J.J. Farrar, and S.I. Hay, 2013: The global distribution and burden of dengue. *Nature*, **496(7446)**, 504-507.

Bi, P. and K.A. Parton, 2008: Effect of climate change on Australian rural and remote regions: what do we know and what do we need to know? *Australian Journal of Rural Health*, **16(1)**, 2-4.

Bi, P., Y. Zhang, and K.A. Parton, 2007: Weather variables and Japanese encephalitis in the metropolitan area of Jinan city, China. *Journal of Infection*, **55(6)**, 551-556.

Black, R.E., L.H. Allen, Z.A. Bhutta, L.E. Caulfield, M.d. Onis, M. Ezzati, C. Mathers, and J. Rivera, 2008: Maternal and child undernutrition: global and regional exposures and health consequences. *Lancet*, **371(9608)**, 243-260.

Boldo, E., C. Linares, J. Lumbreras, R. Borge, A. Narros, J. García-Pérez, P. Fernández-Navarro, B. Pérez-Gómez, N. Aragonés, R. Ramis, M. Pollán, T. Moreno, A. Karanasiou, and G. López-Abente, 2010: Health impact assessment of a reduction in ambient $PM_{2.5}$ levels in Spain. *Environment International*, **37(2)**, 342-348.

Bompangue, N.D., P. Giraudoux, P.D. Plisnier, T.A. Mutombo, M. Piarroux, and B. Sudre, 2011: Dynamics of cholera outbreaks in Great Lakes region of Africa, 1978-2008. *Emerging Infectious Diseases*, **17(11)**, 2026-2034.

Bond, T.C., S.J. Doherty, D.W. Fahey, P.M. Forster, T. Berntsen, B.J. DeAngelo, M.G. Flanner, S. Ghan, B. Kärcher, D. Koch, S. Kinne, Y. Kondo, P.K. Quinn, M.C. Sarofim, M.G. Schultz, M. Schulz, C. Venkataraman, H. Zhang, S. Zhang, N. Bellouin, S.K. Guttikunda, P.K. Hopke, M.Z. Jacobson, J.W. Kaiser, Z. Klimont, U. Lohmann, J.P. Schwarz, D. Shindell, T. Storelvmo, S.G. Warren, and C.S. Zender, 2013: Bounding the role of black carbon in the climate system: a scientific assessment. *Journal of Geophysical Research: Atmospheres*, **118(11)**, 5380-5552.

Bonjour, S., H. Adair-Rohani, J. Wolf, S. Mehta, A. Pruss-Ustun, M. Lahiff, E.A. Rehfuess, V. Mishra, and K.R. Smith, 2013: Solid fuel use for household cooking: country and regional estimates for 1980-2010. *Environmental Health Perspectives*, **121(7)**, 784-790.

Bonovas, S. and G. Nikolopoulos, 2012: High-burden epidemics in Greece in the era of economic crisis. Early signs of a public health tragedy. *Journal of Preventive Medicine and Hygiene*, **53(3)**, 169-171.

Bouchama, A., M. Dehbi, G. Mohamed, F. Matthies, M. Shoukri, and B. Menne, 2007: Prognostic factors in heat wave related deaths: a meta-analysis. *Archives of Internal Medicine*, **167(20)**, 2170-2176.

Bowen, K.J., S. Friel, K. Ebi, C.D. Butler, F. Miller, and A.J. McMichael, 2012: Governing for a healthy population: towards an understanding of how decision-making will determine our global health in a changing climate. *International Journal of Environmental Research and Public Health*, **9(1)**, 55-72.

Brázdil, R., M. Trnka, P. Dobrovolný, K. Chromá, P. Hlavinka, and Z. Žalud, 2009: Variability of droughts in the Czech Republic, 1881-2006. *Theoretical and Applied Climatology*, **97(3-4)**, 297-315.

Breton, M., M. Garneau, I. Fortier, F. Guay, and J. Louis, 2006: Relationship between climate, pollen concentrations of *Ambrosia* and medical consultations for allergic rhinitis in Montreal, 1994-2002. *Science of the Total Environment*, **370(1)**, 39-50.

Brouwer, R., S. Akter, L. Brander, and E. Haque, 2007: Socioeconomic vulnerability and adaptation to environmental risk: a case study of climate change and flooding in Bangladesh. *Risk Analysis*, **27(2)**, 313-326.

Browning, C.R., D. Wallace, S.L. Feinberg, and K.A. Cagney, 2006: Neighborhood social processes, physical conditions, and disaster-related mortality: the case of the 1995 Chicago heat wave. *American Sociological Review*, **71(4)**, 661-678.

Bruce, N., M. Dherani, J. Das, K. Balakrishnan, H. Adair-Rohani, Z. Bhutta, and D. Pope, 2013: Control of household air pollution for child survival: estimates for intervention impacts. *BMC Public Health*, **13(Suppl. 3)**, S8, doi:10.1186/1471-2458-13-S3-S8.

Brunkard, J., G. Namulanda, and R. Ratard, 2008: Hurricane Katrina deaths, Louisiana, 2005. *Disaster Medicine and Public Health Preparedness*, **2(4)**, 215-223.

Bujold, E., S.H. Mehta, C. Bujold, and R.J. Gauthier, 2002: Interdelivery interval and uterine rupture. *American Journal of Obstetrics and Gynecology*, **187(5)**, 1199-1202.

Bulto, P., A.P. Rodriguez, A.R. Valencia, N.L. Vega, M.D. Gonzalez, and A.P. Carrera, 2006: Assessment of human health vulnerability to climate variability and change in Cuba. *Environmental Health Perspectives*, **114(12)**, 1942-1949.

Byass, P., 2010: The imperfect world of global health estimates. *PLoS Medicine*, **7(11)**, e1001006, doi:10.1371/journal.pmed.1001006.

Caminade, C., J.A. Ndione, C.M.F. Kebe, A.E. Jones, S. Danuor, S. Tay, Y.M. Tourre, J. Lacaux, C. Vignolles, J.B. Duchemin, I. Jeanne, and A.P. Morse, 2011: Mapping Rift Valley fever and malaria risk over West Africa using climatic indicators. *Atmospheric Science Letters*, **12(1)**, 96-103.

Caminade, C., J.M. Medlock, E. Ducheyne, K.M. McIntyre, S. Leach, M. Baylis, and A.P. Morse, 2012: Suitability of European climate for the Asian tiger mosquito *Aedes albopictus*: recent trends and future scenarios. *Journal of the Royal Society Interface*, **9(75)**, 2708-2717.

Campbell, J.D., M.A. Taylor, T.S. Stephenson, R.A. Watson, and F.S. Whyte, 2011: Future climate of the Caribbean from a regional climate model. *International Journal of Climatology*, **31(12)**, 1866-1878.

Casagrande, S.S., M.C. Whitt-Glover, K.J. Lancaster, A.M. Odoms-Young, and T.L. Gary, 2009: Built environment and health behaviors among African Americans: a systematic review. *American Journal of Preventive Medicine*, **36(2)**, 174-181.

Casimiro, E., J. Calheiros, F.D. Santos, and R.S. Kovats, 2006: National assessment of health effects of climate change in Portugal: approach and key findings. *Environmental Health Perspectives*, **114(12)**, 1950-1956.

Chadee, D.D., 2009: Dengue cases and *Aedes aegypti* indices in Trinidad, West Indies. *Acta Tropica*, **112(2)**, 174-180.

Chadee, D.D., B. Shivnauth, S.C. Rawlins, and A.A. Chen, 2007: Climate, mosquito indices and the epidemiology of dengue fever in Trinidad (2002-2004). *Annals of Tropical Medicine and Parasitology*, **101(1)**, 69-77.

Chang, H.H., J. Zhou, and M. Fuentes, 2010: Impact of climate change on ambient ozone level and mortality in southeastern United States. *International Journal of Environmental Research and Public Health*, **7(7)**, 2866-2880.

Chang, Y.K., C.C. Wu, L.T. Lee, R.S. Lin, Y.H. Yu, and Y.C. Chen, 2012: The short-term effects of air pollution on adolescent lung function in Taiwan. *Chemosphere*, **87(1)**, 26-30.

Chapman, R.S., X. He, A.E. Blair, and Q. Lan, 2005: Improvement in household stoves and risk of chronic obstructive pulmonary disease in Xuanwei, China: retrospective cohort study. *BMJ*, **331**, 1050, doi:10.1136/bmj.38628.676088.55.

Chau, P.H., K.C. Chan, and J. Woo, 2009: Hot weather warning might help to reduce elderly mortality in Hong Kong. *International Journal of Biometeorology*, **53(5)**, 461-468.

Chaves, L.F. and C.J. Koenraadt, 2010: Climate change and highland malaria: fresh air for a hot debate. *Quarterly Review of Biology*, **85(1)**, 27-55.

Chaves, L.F., A. Satake, M. Hashizume, and N. Minakawa, 2012: Indian Ocean Dipole and rainfall drive a Moran effect in East Africa malaria transmission. *Journal of Infectious Diseases*, **205(12)**, 1885-1891.

Cheng, C.H., S.F. Huang, and H.J. Teoh, 2011: Predicting daily ozone concentration maxima using fuzzy time series based on a two-stage linguistic partition method. *Computers & Mathematics with Applications*, **62(4)**, 2016-2028.

Chowell, G., C.A. Torre, C. Munayco-Escate, L. Suárez-Ognio, R. López-Cruz, J.M. Hyman, and C. Castillo-Chavez, 2008: Spatial and temporal dynamics of dengue fever in Peru: 1994-2006. *Epidemiology & Infection*, **136(12)**, 1667-77.

Chowell, G., B. Cazelles, H. Broutin, and C.V. Munayco, 2011: The influence of geographic and climate factors on the timing of dengue epidemics in Perú, 1994-2008. *BMC Infectious Diseases*, **11**, 164, doi:10.1186/1471-2334-11-164.

Christidis, N., P.A. Stott, G.S. Jones, H. Shiogama, T. Nozawa, and J. Luterbacher, 2012: Human activity and anomalously warm seasons in Europe. *International Journal of Climatology*, **32(2)**, 225-239.

Cleary-Goldman, J., F.D. Malone, J. Vidaver, R.H. Ball, D.A. Nyberg, C.H. Comstock, G.R. Saade, K.A. Eddleman, S. Klugman, L. Dugoff, I.E. Timor-Tritsch, S.D. Craigo, S.R. Carr, H.M. Wolfe, D.W. Bianchi, and M. D'Alton, 2005: Impact of maternal age on obstetric outcome. *Obstetrics & Gynecology*, **105(5 Pt. 1)**, 983-990.

Cohen, J.E., 2010: Population and climate change. *Proceedings of the American Philosophical Society*, **154(2)**, 158-182.

Conde-Agudelo, A., A. Rosas-Bermúdez, and A.C. Kafury-Goeta, 2007: Effects of birth spacing on maternal health: a systematic review. *American Journal of Obstetrics and Gynecology*, **196(4)**, 297-308.

Cook, J.T. and D.A. Frank, 2008: Food security, poverty, and human development in the United States. *Annals of the New York Academy of Sciences*, **1136(1)**, 193-209.

Cook, S.M., R.I. Glass, C.W. LeBaron, and M.S. Ho, 1990: Global seasonality of rotavirus infections. *Bulletin of the World Health Organization*, **68(2)**, 171-177.

Correa, M.d.P., S. Godin-Beekmann, M. Haeffelin, S. Bekki, P. Saiag, J. Badosa, F. Jegou, A. Pazmino, and E. Mahe, 2013: Projected changes in clear-sky erythemal and vitamin D effective UV doses for Europe over the period 2006 to 2100. *Photochemical & Photobiological Sciences*, **12(6)**, 1053-1064.

Danis, K., A. Baka, A. Lenglet, W. Van Bortel, I. Terzaki, M. Tseroni, M. Detsis, E. Papanikolaou, A. Balaska, S. Gewehr, G. Dougas, T. Sideroglou, A. Economopoulou, N. Vakalis, S. Tsiodras, S. Bonovas, and J. Kremastinou, 2011: Autochthonous *Plasmodium vivax* malaria in Greece, 2011. *Eurosurveillance*, **16(42)**, www.eurosurveillance.org/images/dynamic/EE/V16N42/art19993.pdf.

Dasgupta, S., B. Laplante, S. Murray, and D. Wheeler, 2009: *Climate Change and the Future Impacts of Storm-Surge Disasters in Developing Countries*. Working Paper 182, Center for Global Development (CDG), Washington, DC, USA, 22 pp.

Davis, T.W., D.L. Berry, G.L. Boyer, and C.J. Gobler, 2009: The effects of temperature and nutrients on the growth and dynamics of toxic and non-toxic strains of *Microcystis* during cyanobacteria blooms. *Harmful Algae*, **8(5)**, 715-725.

De Haen, H. and G. Hemrich, 2007: The economics of natural disasters: implications and challenges for food security. *Agricultural Economics*, **37**, 31-45.

de Magny, G.C., R. Murtugudde, M.R.P. Sapiano, A. Nizam, C.W. Brown, A.J. Busalacchi, M. Yunus, G.B. Nair, A.I. Gil, C.F. Lanata, J. Calkins, B. Manna, K. Rajendran, M.K. Bhattacharya, A. Huq, R.B. Sack, and R.R. Colwell, 2008: Environmental signatures associated with cholera epidemics. *Proceedings of the National Academy of Sciences of the United States of America*, **105(46)**, 17676-17681.

Dear, K., G. Ranmuthugala, T. Kjellstrom, C. Skinner, and I. Hanigan, 2005: Effects of temperature and ozone on daily mortality during the August 2003 heat wave in France. *Archives of Environmental & Occupational Health*, **60(4)**, 205-212.

Delatte, H., G. Gimonneau, A. Triboire, and D. Fontenille, 2009: Influence of temperature on immature development, survival, longevity, fecundity, and gonotrophic cycles of *Aedes albopictus*, vector of chikungunya and dengue in the Indian Ocean. *Journal of Medical Entomology*, **46(1)**, 33-41.

Delpla, I., A.V. Jung, E. Baures, M. Clement, and O. Thomas, 2009: Impacts of climate change on surface water quality in relation to drinking water production. *Environment International*, **35(8)**, 1225-1233.

Dennekamp, M. and M. Carey, 2010: Air quality and chronic disease: why action on climate change is also good for health. *New South Wales Public Health Bulletin*, **21(5-6)**, 115-121.

Descloux, E., M. Mangeas, C.E. Menkes, M. Lengaigne, A. Leroy, T. Tehei, L. Guillaumot, M. Teurlai, A.C. Gourinat, J. Benzler, A. Pfannstiel, J.P. Grangeon, N. Degallier, and X. De Lamballerie, 2012: Climate-based models for understanding and forecasting dengue epidemics. *PLoS Neglected Tropical Diseases*, **6(2)**, e1470, doi:10.1371/journal.pntd.0001470.

Dey, S.K., H. Ushijima, O. Phathammavong, W. Chanit, S. Okitsu, M. Mizuguchi, and Y. Ota, 2010: Seasonal trend and serotype distribution of rotavirus infection in Japan, 1981-2008. *The Pediatric Infectious Disease Journal*, **29(2)**, 166-167.

Diamond-Smith, N. and M. Potts, 2011: A woman cannot die from a pregnancy she does not have. *International Perspectives on Sexual and Reproductive Health*, **37(3)**, 155-157.

Diboulo, E., A. Sie, J. Rocklov, L. Niamba, M. Ye, C. Bagagnan, and R. Sauerborn, 2012: Weather and mortality: a 10 year retrospective analysis of the Nouna Health and Demographic Surveillance System, Burkina Faso. *Global Health Action*, **5(Suppl. 1)**, 19078, doi:10.3402/gha.v5i0.19078.

Diffenbaugh, N. and F. Giorgi, 2012: Climate change hotspots in the CMIP5 global climate model ensemble. *Climatic Change*, **114(3-4)**, 813-822.

D'Ippoliti, D., P. Michelozzi, C. Marino, F. de'Donato, B. Menne, K. Katsouyanni, U. Kirchmayer, A. Analitis, M. Medina-Ramón, A. Paldy, R. Atkinson, S. Kovats, L. Bisanti, A. Schneider, A. Lefranc, C. Iñiguez, and C.A. Perucci, 2010: The impact of heat waves on mortality in 9 European cities: results from the EuroHEAT project. *Environmental Health*, **9**, 37, doi:10.1186/1476-069X-9-37.

Dix-Cooper, L., B. Eskenazi, C. Romero, J. Balmes, and K.R. Smith, 2012: Neuro-developmental performance among school age children in rural Guatemala is associated with prenatal and postnatal exposure to carbon monoxide, a marker for exposure to woodsmoke. *Neurotoxicology*, **33(2)**, 246-254.

Dodman, D., D. Mitlin, and J.C. Rayos Co, 2010: Victims to victors, disasters to opportunities: community-driven responses to climate change in the Philippines. *International Development Planning Review*, **32(1)**, 1-26, doi:10.3828/idpr.2009.10.

Dong, G.H., T. Chen, M.M. Liu, D. Wang, Y.N. Ma, W.H. Ren, Y.L. Lee, Y.D. Zhao, and Q.C. He, 2011: Gender differences and effect of air pollution on asthma in children with and without allergic predisposition: northeast Chinese children health study. *PLoS One*, **6(7)**, e22470, doi:10.1371/journal.pone.0022470.

Doocy, S., A. Daniels, S. Murray, and T.D. Kirsch, 2013: The human impact of floods: a historical review of events 1980-2009 and systematic literature review. *PLOS Currents Disasters*, 2013 April 16**, Edition 1**, doi:10.1371/currents.dis.f4deb457904936b07c09daa98ee8171a.

Dossou, K. and B. Glehouenou-Dossou, 2007: The vulnerability to climate change of Cotonou (Benin): the rise in sea level. *Environment and Urbanization*, **19**, 65-79.

Doyon, B., D. Belanger, and P. Gosselin, 2008: The potential impact of climate change on annual and seasonal mortality for three cities in Quebec, Canada. *International Journal of Health Geographics*, **7,** 23, doi:10.1186/1476-072X-7-23.

Dunne, J., R. Stouffer, and J. John, 2013: Reductions in labour capacity from heat stress under climate warming. *Nature Climate Change*, **3(3)**, 563-566, doi:10.1038/nclimate1827.

Durand, C.P., M. Andalib, G.F. Dunton, J. Wolch, and M.A. Pentz, 2011: A systematic review of built environment factors related to physical activity and obesity risk: implications for smart growth urban planning. *Obesity Reviews*, **12(5)**, e173-82, doi:10.1111/j.1467-789X.2010.00826.x.

Earnest, A., S.B. Tan, and A. Wilder-Smith, 2012: Meteorological factors and El Nino Southern Oscillation are independently associated with dengue infections. *Epidemiology & Infection*, **140(7)**, 1244-1251.

Ebi, K.L. and G. McGregor, 2008: Climate change, tropospheric ozone and particulate matter, health impacts. *Environmental Health Perspectives*, **116(11)**, 1449-1455.

Ebi, K.L. and D. Mills, 2013: Winter mortality in a warming world: a re-assessment. *WIREs Climate Change*, **4**, 203-212.

Ebi, K.L., K.A. Exuzides, E. Lau, M. Kelsh, and A. Barnston, 2004: Weather changes associated with hospitalizations for cardiovascular diseases and stroke in California, 1983-1998. *International Journal of Biometeorology*, **49(1)**, 48-58.

Ebi, K.L., J. Smith, I. Burton, and J. Scheraga, 2006: Some lessons learned from public health on the process of adaptation. *Mitigation Adaptation Strategies Global Change*, **11**, 607-620.

Edwards, R.D., K.R. Smith, J. Zhang, and Y. Ma, 2004: Implications of changes in household stoves and fuel use in China. *Energy Policy*, **32(3)**, 395-411.

Engelman, R., 2010: *Population, Climate Change, and Women's Lives.* Worldwatch Report No.183, Worldwatch Institute, Washington, DC, USA, 44 pp.

EPA, 2010: *Air Quality Trends*. United States Environmental Protection Agency (EPA), Washington, DC, USA, last updated September 3, 2013, www.epa.gov/airtrends/aqtrends.html.

Erdner, D.L., J. Dyble, M.L. Parsons, R.C. Stevens, K.A. Hubbard, M.L. Wrabel, S.K. Moore, K.A. Lefebvre, D.M. Anderson, P. Bienfang, R.R. Bidigare, M.S. Parker, P. Moeller, L.E. Brand, and V.L. Trainer, 2008: Centers for Oceans and Human Health: a unified approach to the challenge of harmful algal blooms. *Environmental Health*, **7 (Suppl. 2)**, S2, www.ehjournal.net/content/7/S2/S2.

Estrada-Peña, A., N. Ayllón, and J. de la Fuente, 2012: Impact of climate trends on tick-borne pathogen transmission. *Frontiers in Physiology*, **3**, 64, doi:10.3389/fphys.2012.00064.

Ezzine-de-Blas, D., J. Börner, A. Violato-Espada, N. Nascimento, and M. Piketty, 2011: Forest loss and management in land reform settlements: implications for REDD governance in the Brazilian Amazon. *Environmental Science & Policy*, **14(2)**, 188-200.

Fang, L.Q., X.J. Wang, S. Liang, Y.L. Li, S.X. Song, W.Y. Zhang, Q. Qian, Y.P. Li, L. Wei, Z.Q. Wang, H. Yang, and W.C. Cao, 2010: Spatiotemporal trends and climatic factors of hemorrhagic fever with renal syndrome epidemic in Shandong Province, China. *PLoS Neglected Tropical Diseases*, **4(8)**, e789, doi:10.1371/journal.pntd.0000789.

Feachem, R.G., A.A. Phillips, J. Hwang, C. Cotter, B. Wielgosz, B.M. Greenwood, O. Sabot, M.H. Rodriguez, R.R. Abeyasinghe, T.A. Ghebreyesus, R.W Snow, 2010: Shrinking the malaria map: progress and prospects. *Lancet*, **376(9752)**, 1566–1578.

Finlay, S., A. Moffat, R. Gazzard, D. Baker, and V. Murray, 2012: Health impacts of wildfires. *PLoS Currents*, 2012 November 2, **Edition 1**, doi:10.1371/4f959951cce2c.

Finucane, M.M., G.A. Stevens, M.J. Cowan, G. Danaei, J.K. Lin, C.J. Paciorek, G.M. Singh, H.R. Gutierrez, Y. Lu, A.N. Bahalim, F. Farzadfar, L.M. Riley, M. Ezzati, and the Global Burden of Metabolic Risk Factors of Chronic Diseases Collaborating Group (Body Mass Index), 2011: National, regional, and global trends in body-mass index since 1980: systematic analysis of health examination surveys and epidemiological studies with 960 country-years and 9.1 million participants. *Lancet*, **377(9765)**, 557-567.

Foley, J.A., N. Ramankutty, K.A. Brauman, E.S. Cassidy, J.S. Gerber, M. Johnston, N.D. Mueller, C. O'Connell, D.K. Ray, P.C. West, C. Balzer, E.M. Bennett, S.R. Carpenter, J. Hill, C. Monfreda, S. Polasky, J. Rockström, J. Sheehan, S. Siebert, D. Tilman, and D.P.M. Zaks, 2011: Solutions for a cultivated planet. *Nature*, **337(7369)**, 337-342.

Ford, J.D., 2009: Vulnerability of Inuit food systems to food insecurity as a consequence of climate change: a case study from Igloolik, Nunavut. *Regional Environmental Change*, **9(2)**, 83-100.

Ford, J.D., T. Pearce, J. Gilligan, B. Smit, and J. Oakes, 2008: Climate change and hazards associated with ice use in northern Canada. *Arctic, Antarctic, and Alpine Research*, **40(4)**, 647-659.

Fouillet, A., G. Rey, F. Laurent, G. Pavillon, S. Bellec, C. Guihenneuc-Jouyaux, J. Clavel, E. Jougla, and D. Hémon, 2006: Excess mortality related to the August 2003 heat wave in France. *International Archives of Occupational & Environmental Health*, **80(1)**, 16-24.

Fouillet, A., G. Rey, V. Wagner, K. Laaidi, P. Empereur-Bissonnet, A. Le Tertre, P. Frayssinet, P. Bessemoulin, F. Laurent, P. De Crouy-Chanel, E. Jougla, and D. Hémon, 2008: Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave. *International Journal of Epidemiology*, **37(2)**, 309-317.

Friel, S., M. Marmot, A.J. McMichael, T. Kjellstrom, and D. Vagero, 2008: Global health equity and climate stabilisation: a common agenda. *Lancet*, **372(9650)**, 1677-1683.

Friel, S., A.D. Dangour, T. Garnett, K. Lock, Z. Chalabi, I. Roberts, A. Butler, C.D. Butler, J. Waage, A.J. McMichael, and A. Haines, 2009: Public health benefits of strategies to reduce greenhouse-gas emissions: food and agriculture. *Lancet*, **374(9706)**, 2016-2025.

Frumkin, H. and A.J. McMichael, 2008: Climate change and public health: thinking, communicating, acting. *American Journal of Preventive Medicine*, **35(5)**, 403-410.

Frumkin, H., J. Hess, G. Luber, J. Malilay, and M. McGeehin, 2008: Climate change: the public health response. *American Journal of Public Health*, **98(3)**, 435-445.

Gamble, J.L., B.J. Hurley, P.A. Schultz, W.S. Jaglom, N. Krishnan, and M. Harris, 2013: Climate change and older Americans: state of the science. *Environmental Health Perspectives*, **121(1)**, 15-22.

Gasparrini, A. and B. Armstrong, 2011: The impact of heat waves on mortality. *Epidemiology*, **22(1)**, 68-73.

Ge, C., C. Lee, and J. Lee, 2012: The impact of extreme weather events on *Salmonella* internalization in lettuce and green onion. *Food Research International*, **45(2)**, 1118-1122.

GEA, 2012: *Global Energy Assessment – Toward a Sustainable Future.* The International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria and Cambridge University Press, Cambridge, UK and New York, NY, USA, 1865 pp.

Gemenne, F., 2011: Climate-induced population displacements in a 4°C+ world. *Philosophical Transactions of the Royal Society A*, **369(1934)**, 182-195.

Gething, P.W., D.L. Smith, A.P. Patil, A.J. Tatem, R.W. Snow, and S.I. Hay, 2010: Climate change and the global malaria recession. *Nature*, **465(7296)**, 342-345.

Gharbi, M., P. Quenel, J. Gustave, S. Cassadou, G. La Ruche, L. Girdary, and L. Marrama, 2011: Time series analysis of dengue incidence in Guadeloupe, French West Indies: forecasting models using climate variables as predictors. *BMC Infectious Diseases*, **11**, 166, doi:10.1186/1471-2334-11-166.

Gosling, S.N., G.R. Mcgregor, and J.A. Lowe, 2009: Climate change and heat-related mortality in six cities Part 2: climate model evaluation and projected impacts from changes in the mean and variability of temperature with climate change. *International Journal of Biometeorology*, **53(1)**, 31-51.

Grabow, M.L., S.N. Spak, T. Holloway, B. Stone Jr., A.C. Mednick, and J.A. Patz, 2011: Air quality and exercise-related health benefits from reduced car travel in the midwestern United States. *Environmental Health Perspectives*, **120(1)**, 68-76.

Grace, K., F. Davenport, C. Funk, and A.M. Lerner, 2012: Child malnutrition and climate in sub-Saharan Africa: an analysis of recent trends in Kenya. *Applied Geography*, **35(1-2)**, 405-413.

Gray, J.S., H. Dautel, A. Estrada-Pena, O. Kahl, and E. Lindgren, 2009: Effects of climate change on ticks and tick-borne diseases in Europe. *Interdisciplinary Perspectives on Infectious Diseases*, **2009**, 593232, doi:10.1155/2009/593232.

Green, R., L. Cornelsen, A.D. Dangour, R. Turner, B. Shankar, M. Mazzocchi, and R.D. Smith, 2013: The effect of rising food prices on food consumption: systematic review with meta-regression. *BMJ*, **346**, f3703, doi:10.1136/bmj.f3703.

Gribble, J.N., N.J. Murray, and E.P. Menotti, 2009: Reconsidering childhood undernutrition: can birth spacing make a difference? An analysis of the 2002-2003 El Salvador National Family Health Survey. *Maternal & Child Nutrition*, **5(1)**, 49-63.

Gubler, D.J. and G. Kuno, 1997: *Dengue and Dengue Haemorrhagic Fever.* CAB International (CABI), Wallingford, UK, 478 pp.

Guha-Sapir, D., F. Vos, and R. Below, 2011: *Annual Disaster Statistical Review 2010: The Numbers and Trends.* Center for Research on the Epidemiology of Disasters (CRED), Université catholique de Louvain, Brussels, Belgium, 42 pp.

Ha, J., H. Kim, and S. Hajat, 2011: Effect of previous-winter mortality on the association between summer temperature and mortality in South Korea. *Environmental Health Perspectives*, **119(4)**, 542-546.

Haines, A., K.R. Smith, D. Anderson, P.R. Epstein, A.J. McMichael, I. Roberts, P. Wilkinson, J. Woodcock, and J. Woods, 2007: Policies for accelerating access to clean energy, improving health, advancing development, and mitigating climate change. *Lancet*, **370(9594)**, 1264-1281.

Haines, A., A. McMichael, K. Smith, I. Roberts, J. Woodcock, A. Markandya, B. Armstrong, D. Campbell-Lendrum, A. Dangour, M. Davies, N. Bruce, C. Tonne, M. Barrett, and P. Wilkinson, 2009: Public health benefits of strategies to reduce greenhouse-gas emissions: overview and implications for policy makers. *Lancet*, **374(9707)**, 2104-2114.

Hajat, S., M. O'Connor, and T. Kosatsky, 2010: Health effects of hot weather: from awareness of risk factors to effective health protection. *Lancet*, **375(9717)**, 856-863.

Halide, H. and P. Ridd, 2008: A predictive model for Dengue Hemorrhagic Fever epidemics. *International Journal of Environmental Health*, **18(4)**, 253-265.

Hancock, P., J. Ross, and J. Szalma, 2007: A meta-analysis of performance response under thermal stressors. *Human Factors*, **49**, 851-877.

Handmer, J., Y. Honda, Z.W. Kundzewicz, N. Arnell, G. Benito, J. Hatfield, I.F. Mohamed, P. Peduzzi, S. Wu, B. Sherstyukov, and K. Takahashi, 2012: Changes in impacts of climate extremes: human systems and ecosystems. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 231-290.

Hanigan, I.C., C.D. Butler, P.N. Kokic, and M.F. Hutchinson, 2012: Suicide and drought in New South Wales, Australia, 1970-2007. *Proceedings of the National Academy of Sciences of the United States of America*, **109(35)**, 13950-13955.

Hanna, E.G., T. Kjellstrom, C. Bennett, and K. Dear, 2011: Climate change and rising heat: population health implications for working people in Australia. *Asia-Pacific Journal of Public Health*, **23(2 Suppl.)**, 14S-26S.

Hansen, A.L., P. Bi, P. Ryan, M. Nitschke, D. Pisaniello, and G. Tucker, 2008: The effect of heat waves on hospital admissions for renal disease in a temperate city of Australia. *International Journal of Epidemiology*, **37(6)**, 1359-1365.

Hashizume, M., 2008: Factors determining vulnerability to diarrhoea during and after severe floods in Bangladesh. *Journal of Water and Health*, **6(3)**, 323-332, doi:10.2166/wh.2008.062.

Hashizume, M. and A.M. Dewan, 2012: Hydroclimatological variability and dengue transmission in Dhaka, Bangladesh: a time-series study. *BMC Infectious Diseases*, **12(1)**, 98, doi:10.1186/1471-2334-12-98.

Health Protection Agency, 2012: *Health Effects of Climate Change in the UK 2012: Current Evidence, Recommendations and Research Gaps* [Vardoulakis, S. and C. Heaviside (eds.)]. Health Protection Agency, Public Health England, UK Government Department of Health, London, UK, 236 pp.

Heguy, L., M. Garneau, M.S. Goldberg, M. Raphoz, F. Guay, and M. Valois, 2008: Associations between grass and weed pollen and emergency department visits for asthma among children in Montreal. *Environmental Research*, **106(2)**, 203-211.

Herrera-Martinez, A.D. and A.J. Rodriguez-Morales, 2010: Potential influence of climate variability on dengue incidence registered in a western pediatric hospital of Venezuela. *Tropical Biomedicine*, **27(2)**, 280-286.

Hess, J.J., 2008: Climate change: the importance of place. *American Journal of Preventive Medicine*, **35(5)**, 468-478.

Hesterberg, T.W., W.B. Bunn, R.O. McClellan, A.K. Hamade, C.M. Long, and P.A. Valberg, 2009: Critical review of the human data on short-term nitrogen dioxide (NO_2) exposures: evidence for NO_2 no-effect levels. *Critical Reviews in Toxicology*, **39(9)**, 743-781.

Hii, Y.L., J. Rocklov, N. Ng, C.S. Tang, F.Y. Pang, and R. Sauerborn, 2009: Climate variability and increase in intensity and magnitude of dengue incidence in Singapore. *Global Health Action*, **2**, doi:10.3402/gha.v2i0.2036.

Hii, Y.L., J. Rocklov, and N. Ng, 2011: Short term effects of weather on hand, foot and mouth disease. *PLoS One*, **6(2)**, e16796, doi:10.1371/journal.pone.0016796.

Hii, Y.L., H. Zhu, N. Ng, L.C. Ng, and J. Rocklov, 2012: Forecast of dengue incidence using temperature and rainfall. *PLoS Neglected Tropical Diseases*, **6(11)**, e1908, doi:10.1371/journal.pntd.0001908.

Holmes, J., 2010: The forestry industry. In: *What Do We Know? What Do We Need to Know? The State of Canadian Research on Work, Employment and Climate Change* [Lipsig-Mummé, C. (ed.)]. Work in a Warming World Research Programme, Institute for Research and Innovation in Sustainability (IRIS), York University, Toronto, ON, Canada, pp. 148-166.

Holt, A.C., D.J. Salkeld, C.L. Fritz, J.R. Tucker, and P. Gong, 2009: Spatial analysis of plague in California: niche modeling predictions of the current distribution and potential response to climate change. *International Journal of Health Geographics*, **8**, 38, doi:10.1186/1476-072X-8-38.

Honda, Y., M. Kondo, G. McGregor, H. Kim, Y. Guo, Y. Hijioka, M. Yoshikawa, K. Oka, S. Takano, S. Hales, and R.S. Kovats, 2013: Heat-related mortality risk model for climate change impact projection. *Environmental Health and Preventive Medicine*, doi:10.1007/s12199-013-0354-6.

Hondula, D.M., J. Rocklov, and O.A. Sankoh, 2012: Past, present, and future climate at select INDEPTH member Health and Demographic Surveillance Systems in Africa and Asia. *Global Health Action*, **5**, 74-86.

Hooper, L., C.D. Summerbell, R. Thompson, D. Sills, F.G. Roberts, H.J. Moore, and G. Davey Smith, 2012: Reduced or modified dietary fat for preventing cardiovascular disease (Review). *Cochrane Database of Systematic Reviews*, **5**, CD002137, doi:10.1002/14651858.CD002137.pub3.

Hosking, J. and D. Campbell-Lendrum, 2012: How well does climate change and human health research match the demands of policymakers? A scoping review. *Environmental Health Perspectives*, **120(8)**, 1076-1082.

Hsieh, Y.H. and C.W. Chen, 2009: Turning points, reproduction number, and impact of climatological events for multi-wave dengue outbreaks. *Tropical Medicine & International Health*, **14(6)**, 628-638.

Huang, C., A.G. Barnett, X. Wang, P. Vaneckova, G. FitzGerald, and S. Tong, 2011: Projecting future heat-related mortality under climate change scenarios: a systematic review. *Environmental Health Perspectives*, **119(12)**, 1681-1690.

Huang, C., A.G. Barnett, X. Wang, and S. Tong, 2012: The impact of temperature on years of life lost in Brisbane, Australia. *Nature Climate Change*, **2(4)**, 265-270.

Hughes, B.B., R. Kuhn, C.M. Peterson, D.S. Rothman, J.R. Solorzano, C.D. Mathers, and J.R. Dickson, 2011: Projections of global health outcomes from 2005 to 2060 using the International Futures integrated forecasting model. *Bulletin of the World Health Organization*, **89(7)**, 478-486.

IFAD, 2010: *Rural Poverty Report 2011: New Realities, New Challenges: New Opportunities for Tomorrow's Generation.* International Fund for Agricultural Development (IFAD), Rome, Italy, 319 pp.

ILO, 2013: *Global Employment Trends 2013: Recovering from a Second Jobs Dip.* International Labour Organization (ILO), Geneva, Switzerland, 170 pp.

IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 996 pp.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp.

Islam, M.S., 2009: Effects of local climate variability on transmission dynamics of cholera in Matlab, Bangladesh. *Transactions of the Royal Society of Tropical Medicine and Hygiene*, **103(11)**, 1165-1170.

ISO, 1989: *Hot Environments – Estimation of the Heat Stress on Working Man, Based on the WBGT-Index (Wet Bulb Globe Temperature).* International Standard ISO Standard 7243: 1989 E, 2nd edn., International Organization for Standardization, Geneva, Switzerland, 16 pp.

Jackson, J.E., M.G. Yost, C. Karr, C. Fitzpatrick, B.K. Lamb, S.H. Chung, J. Chen, J. Avise, R.A. Rosenblatt, and R.A. Fenske, 2010: Public health impacts of climate change in Washington State: projected mortality risks due to heat events and air pollution. *Climate Change*, **102(1-2)**, 159-186.

Jacobson, M.Z., 2009: Review of solutions to global warming, air pollution, and energy security. *Energy & Environmental Science*, **(2)**, 148-173.

Jacobson, M.Z., 2010: Short-term effects of controlling fossil-fuel soot, biofuel soot and gases, and methane on climate, Arctic ice, and air pollution health. *Journal of Geophysical Research: Atmospheres*, **115(D14)**, D14209, doi:10.1029/2009JD013795.

Jacobson, M.Z., R.W. Howarth, M.A. Delucchi, S.R. Scobie, J.M. Barth, M.J. Dvorak, M. Klevze, H. Katkhuda, B. Miranda, N.A. Chowdhury, R. Jones, L. Plano, and A.R. Ingraffea, 2013: Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight. *Energy Policy*, **57**, 585-601.

Jaenson, T., D. Jaenson, L. Eisen, E. Petersson, and E. Lindgren, 2012: Changes in the geographical distribution and abundance of the tick *Ixodes ricinus* during the past 30 years in Sweden. *Parasites & Vectors*, **5(1)**, 8, doi:10.1186/1756-3305-5-8.

Jakszyn, P., C.A. González, L. Luján-Barroso, M.M. Ros, H.B. Bueno-de-Mesquita, N. Roswall, A.M. Tjønneland, F.L. Büchner, L. Egevad, K. Overvad, O. Raaschou-Nielsen, F. Clavel-Chapelon, M. Boutron-Ruault, M.S. Touillaud, J. Chang-Claude, N.E. Allen, L.A. Kiemeney, T.J. Key, R. Kaaks, H. Boeing, S. Weikert, A. Trichopoulou, E. Oikonomou, D. Zylis, D. Palli, F. Berrino, P. Vineis, R. Tumino, A. Mattiello, P.H.M. Peeters, C.L. Parr, I.T. Gram, G. Skeie, M. Sánchez, N. Larrañaga, E. Ardanaz, C. Navarro, L. Rodríguez, D. Ulmert, R. Ehrnström, G. Hallmans, B. Ljungberg, A.W. Roddam, S.A. Bingham, K. Khaw, N. Slimani, P.A. Boffetta, M. Jenab, T. Mouw, D.S. Michaud, and E. Riboli, 2011: Red meat, dietary nitrosamines, and heme iron and risk of bladder cancer in the European Prospective Investigation into Cancer and Nutrition (EPIC). *Cancer Epidemiology Biomarkers & Prevention*, **20(3)**, 555-559.

Jakubicka, T., F. Vos, R. Phalkey, M. Marx, and D. Guha-Sapir, 2010: *Health Impacts of Floods in Europe: Data Gaps and Information Needs from a Spatial Perspective.* A MICRODIS Project Report, Universitätsklinikum, Heidelberg, Institut für Public Health, Heidelberg, Germany and the Center for Research on the Epidemiology of Disasters (CRED), Université catholique de Louvain (UCL), Brussels, Belgium, 42 pp.

Jamison, D.T., J.G. Breman, A.R. Measham, G. Alleyne, M. Claeson, D.B. Evans, J. Prabhat, A. Mills, and P. Musgrove (eds.), 2006: *Disease Control Priorities in Developing Countries*. 2nd edn., The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA and Oxford University Press, New York, NY, USA, 1401 pp.

Jankowska, M.M., D. Lopez-Carr, C. Funk, and Z.A. Chafe, 2012: Climate change and human health: spatial modeling availability, malnutrition, and livelihoods in Mali, Africa. *Applied Geography*, **33**, 4-15.

Jarrett, J., J. Woodcock, U.K. Griffiths, Z. Chalabi, P. Edwards, I. Roberts, and A. Haines, 2012: Effect of increasing active travel in urban England and Wales on costs to the National Health Service. *Lancet*, **379(9832)**, 2198-2205.

Jensen, H., M. Keogh-Brown, R. Smith, Z. Chalabi, A. Dangour, M. Davies, P. Edwards, T. Garnett, M. Givoni, U. Griffiths, I. Hamilton, J. Jarrett, I. Roberts, P. Wilkinson, J. Woodcock, and A. Haines, 2013: The importance of health co-benefits in macroeconomic assessments of UK Greenhouse Gas emission reduction strategies. *Climatic Change*, **121(2)**, 223-237.

Jerrett, M., R.T. Burnett, C.A. Pope 3rd, K. Ito, G. Thurston, D. Krewski, Y. Shi, E. Calle, and M. Thun, 2009: Long-term ozone exposure and mortality. *The New England Journal of Medicine*, **360(11)**, 1085-1095.

Johnston, F., S. Henderson, Y. Chen, J. Randerson, M. Marlier, R. DeFries, P. Kinney, D. Bowman, and B. M, 2012: Estimated global mortality attributable to smoke from landscape fires. *Environmental Health Perspectives*, **120(5)**, 695-701.

Jonkman, S.N. and I. Kelman, 2005: An analysis of the causes and circumstances of flood disaster deaths. *Disasters*, **29(1)**, 75-97.

Kaczynski, A.T. and K.A. Henderson, 2008: Parks and recreation settings and active living: a review of associations with physical activity function and intensity. *Journal of Physical Activity & Health*, **5(4)**, 619-632.

Karanikolos, M., P. Mladovsky, J. Cylus, S. Thomson, S. Basu, D. Stuckler, J.P. Mackenbach, and M. McKee, 2013: Financial crisis, austerity, and health in Europe. *Lancet*, **381(9874)**, 1323-1331.

Kearney, M., W.P. Porter, C. Williams, S. Ritchie, and A.A. Hoffmann, 2009: Integrating biophysical models and evolutionary theory to predict climatic impacts on species' ranges: the dengue mosquito *Aedes aegypti* in Australia. *Functional Ecology*, **23(3)**, 528-538.

Keim, M.E., 2008: Building human resilience: the role of public health preparedness and response as an adaptation to climate change. *American Journal of Preventive Medicine*, **35(5)**, 508-516.

Kellenberg, D.K. and A.M. Mobarak, 2008: Does rising income increase or decrease damage risk from natural disasters? *Journal of Urban Economics*, **63(3)**, 788-802.

Kelly-Hope, L.A., J. Hemingway, and F.E. McKenzie, 2009: Environmental factors associated with the malaria vectors *Anopheles gambiae* and *Anopheles funestus* in Kenya. *Malaria Journal*, **8**, 268, doi:10.1186/1475-2875-8-2681-8.

Kessler, R.C., S. Galea, M.J. Gruber, N.A. Sampson, R.J. Ursano, and S. Wessely, 2008: Trends in mental illness and suicidality after Hurricane Katrina. *Molecular Psychiatry*, **13(4)**, 374-384.

Khan, M.S.A., 2008: Disaster preparedness for sustainable development in Bangladesh. *Disaster Prevention and Management*, **17(5)**, 662-671.

Khetsuriani, N., A. LaMonte-Fowlkes, M.S. Oberste, and M.A. Pallansch, 2006: Enterovirus surveillance – United States, 1970-2005. *MMWR Surveillance Summaries*, **55(SS-8)**, 1-20.

Kim, Y., H. Kim, and D.S. Kim, 2011: Association between daily environmental temperature and suicide mortality in Korea (2001-2005). *Psychiatry Research*, **186(2-3)**, 390-396.

Kinney, P.L., M. Pascal, R. Vautard, and K. Laaidi, 2012: La mortalite hivernale va-t-elle diminuer avec le changement climatique? [Winter mortality in a changing climate: will it go down?]. *Bulletin épidémiologique hebdomadaire*, **(12-13)**, 149-151.

Kinney, P.L., M.S. O'Neill, M.L. Bell, and J. Schwartz, 2008: Approaches for estimating effects of climate change on heat-related deaths: challenges and opportunities. *Environmental Science & Policy*, **11(1)**, 87-96.

Kite-Powell, H.L., L.E. Fleming, L.C. Backer, E.M. Faustman, P. Hoagland, A. Tsuchiya, L.R. Younglove, B.A. Wilcox, and R.J. Gast, 2008: Linking the oceans to public health: current efforts and future directions. *Environmental Health*, **7(Suppl. 2)**, S6, doi:10.1186/1476-069X-7-S2-S6.

Kjellstrom, T. and J. Crowe, 2011: Climate change, workplace heat exposure, and occupational health and productivity in Central America. *International Journal of Occupational & Environmental Health*, **17(3)**, 270-281.

Kjellstrom, T., I. Holmer, and B. Lemke, 2009a: Workplace heat stress, health and productivity – an increasing challenge for low and middle-income countries during climate change. *Global Health Action*, **2(1)**, 6, doi:10.3402/gha.v2i0.2047.

Kjellstrom, T., R.S. Kovats, S.J. Lloyd, T. Holt, and R.S. Tol, 2009b: The direct impact of climate change on regional labor productivity. *Archives of Environmental and Occupational Health*, **64(4)**, 217-227, doi:10.1080/19338240903352776.

Kjellstrom, T., B. Lemke, and O. Hyatt, 2011: Increased workplace heat exposure due to climate change. *Asia-Pacific Newsletter on Occupational Health and Safety*, **(18)**, 6-20.

Kjellstrom, T., B. Lemke, and M. Otto, 2013: Mapping occupational heat exposure and effects in South-East Asia: ongoing time trends 1980-2009 and future estimates to 2050. *Industrial Health*, **51**, 56-67.

Knowlton, K., B. Lynn, R.A. Goldberg, C. Rosenzweig, C. Hogrefe, J.K. Rosenthal, and P.L. Kinney, 2007: Projecting heat-related mortality impacts under a changing climate in the New York City region. *American Journal of Public Health*, **97(11)**, 2028-2034.

Knowlton, K., M. Rotkin-Ellman, G. King, H.G. Margolis, D. Smith, G. Solomon, R. Trent, and P. English, 2009: The 2006 California heat wave: impacts on hospitalizations and emergency department visits. *Environmental Health Perspectives*, **117(1)**, 61-67.

Knox, J., T. Hess, A. Daccache, and T. Wheeler, 2012: Climate change impacts on crop productivity in Africa and South Asia. *Environmental Research Letters*, **7(3)**, 034032, doi:10.1088/1748-9326/7/3/034032.

Kolstad, E. and K.A. Johansson, 2011: Uncertainties associated with quantifying climate change impacts on human health: a case study for diarrhea. *Environmental Health Perspectives*, **119(3)**, 299-305.

Kosatsky, T., 2005: The 2003 European heat waves. *Eurosurveillance*, **10(7)**, 148-149.

Kovats, R.S. and S. Hajat, 2008: Heat stress and public health: a critical review. *Annual Review of Public Health*, **29**, 41-55.

Kovats, R.S., S.J. Edwards, S. Hajat, B.G. Armstrong, and K.L. Ebi, 2004: The effect of temperature on food poisoning: a time-series analysis of salmonellosis in ten European countries. *Epidemiology and Infection*, **132**, 443-453.

Kozuki, N., A. Lee, M. Silveira, C. Victora, L. Adair, J. Humphrey, R. Ntozini, R. Black, J. Katz, and Child Health Epidemiology Reference Group Small-for-Gestational-Age-Preterm Birth, Working Group, 2013: The associations of birth intervals with small-for-gestational-age, preterm, and neonatal and infant mortality: a meta-analysis. *BMC Public Health*, **13(Suppl. 3)**, S3, doi:10.1186/1471-2458-13-S3-S3.

Kriz, B., M. Maly, C. Benes, and M. Daniel, 2012: Epidemiology of tick-borne encephalitis in the Czech Republic 1970-2008. *Vector-Borne and Zoonotic Diseases*, **12(11)**, 994-999.

Lai, L.W., 2011: Influence of environmental conditions on asynchronous outbreaks of dengue disease and increasing vector population in Kaohsiung, Taiwan. *International Journal of Environmental Health Research*, **21**, 133-146.

Lake, I.R., 2009: A re-evaluation of the impact of temperature and climate change on foodborne illness. *Epidemiology and Infection*, **137(11)**, 1538-1547.

Lake, I.R., L. Hooper, A. Abdelhamid, G. Bentham, A.B.A. Boxall, A. Draper, S. Fairweather-Tait, M. Hulme, P.R. Hunter, G. Nichols, and K.W. Waldron, 2012: Climate change and food security: health impacts in developed countries. *Environmental Health Perspectives*, **120(11)**, 1520-1526.

Lam, N.L., Y. Chen, C. Weyant, C. Venkataraman, P. Sadavarte, M.A. Johnson, K.R. Smith, B.T. Brem, J. Arineitwe, J.E. Ellis, and T.C. Bond, 2012: Household light makes global heat: high black carbon emissions from kerosene wick lamps. *Environmental Science & Technology*, **46(24)**, 13531-13538.

Lan, Q., R.S. Chapman, D.M. Schreinemachers, L. Tian, and X. He, 2002: Household stove improvement and risk of lung cancer in Xuanwei, China. *Journal of the National Cancer Institute*, **94(11)**, 826-835.

Lecocq, F. and Z. Shalizi, 2007: *Balancing Expenditures on Mitigation of and Adaptation to Climate Change: An Exploration of Issues Relevant to Developing Countries.* Policy Research Working Paper 4299, The World Bank Development Research Group, Sustainable Rural and Urban Development Team, Washington, DC, USA, 42 pp.

Lefohn, A.S., D. Shadwick, and S.J. Oltmans, 2010: Characterizing changes in surface ozone levels in metropolitan and rural areas in the United States for 1980-2008 and 1994-2008. *Atmospheric Environment*, **44(39)**, 5199-5210.

Lemke, B. and T. Kjellstrom, 2012: Calculating workplace WBGT from meteorological data: a tool for climate change assessment. *Industrial Health*, **50(4)**, 267-278.

Lepeule, J., F. Laden, D. Dockery, and J. Schwartz, 2012: Chronic exposure to fine particles and mortality: an extended follow-up of the Harvard Six Cities Study from 1974 to 2009. *Environmental Health Perspectives*, **120(7)**, 965-970.

Li, S., H. Tao, and Y. Xu, 2011: Abiotic determinants to the spatial dynamics of dengue fever in Guangzhou. *Asia-Pacific Journal of Public Health*, **25(3)**, 239-247.

Likhvar, V., Y. Honda, and M. Ono, 2011: Relation between temperature and suicide mortality in Japan in the presence of other confounding factors using time-series analysis with a semiparametric approach. *Environmental Health and Preventive Medicine*, **16(1)**, 36-43.

Lim, S.S., T. Vos, A.D. Flaxman, G. Danaei, K. Shibuya, H. Adair-Rohani, M.A. AlMazroa, M. Amann, H.R. Anderson, K.G. Andrews, M. Aryee, C. Atkinson, L.J. Bacchus, A.N. Bahalim, K. Balakrishnan, J. Balmes, S. Barker-Collo, A. Baxter, M.L. Bell, J.D. Blore, F. Blyth, C. Bonner, G. Borges, R. Bourne, M. Boussinesq, M. Brauer, P. Brooks, N.G. Bruce, B. Brunekreef, C. Bryan-Hancock, C. Bucello, R. Buchbinder, F. Bull, R.T. Burnett, T.E. Byers, B. Calabria, J. Carapetis, E. Carnahan, Z. Chafe, F. Charlson, H. Chen, J.S. Chen, A.T. Cheng, J.C. Child, A. Cohen, K.E. Colson, B.C. Cowie, S. Darby, S. Darling, A. Davis, L. Degenhardt, F. Dentener, D. Des Jarlais C., K. Devries, M. Dherani, E.L. Ding, E.R. Dorsey, T. Driscoll, K. Edmond, S.E. Ali, R.E. Engell, P.J. Erwin, S. Fahimi, G. Falder, F. Farzadfar, A. Ferrari, M.M. Finucane, S. Flaxman, F.G.R. Fowkes, G. Freedman, M.K. Freeman, E. Gakidou, S. Ghosh, E. Giovannucci, G. Gmel, K. Graham, R. Grainger, B. Grant, D. Gunnell, H.R. Gutierrez, W. Hall, H.W. Hoek, A. Hogan, H.D. Hosgood, D. Hoy, H. Hu, B.J. Hubbell, S.J. Hutchings, S.E. Ibeanusi, G.L. Jacklyn, R. Jasrasaria, J.B. Jonas, H. Kan, J.A. Kanis, N. Kassebaum, N. Kawakami, Y. Khang, S. Khatibzadeh, J. Khoo, C. Kok, F. Laden, R. Lalloo, Q. Lan, T. Lathlean, J.L. Leasher, J. Leigh, Y. Li, J.K. Lin,

S.E. Lipshultz, S. London, R. Lozano, Y. Lu, J. Mak, R. Malekzadeh, L. Mallinger, W. Marcenes, L. March, R. Marks, R. Martin, P. McGale, J. McGrath, S. Mehta, Z.A. Memish, G.A. Mensah, T.R. Merriman, R. Micha, C. Michaud, V. Mishra, K.M. Hanafiah, A.A. Mokdad, L. Morawska, D. Mozaffarian, T. Murphy, M. Naghavi, B. Neal, P.K. Nelson, J.M. Nolla, R. Norman, C. Olives, S.B. Omer, J. Orchard, R. Osborne, B. Ostro, A. Page, K.D. Pandey, C.D.H. Parry, E. Passmore, J. Patra, N. Pearce, P.M. Pelizzari, M. Petzold, M.R. Phillips, D. Pope, C.A. Pope, J. Powles, M. Rao, H. Razavi, E.A. Rehfuess, J. Rehm, B. Ritz, F.P. Rivara, T. Roberts, C. Robinson, J. Rodriguez-Portales, I. Romieu, R. Room, L.C. Rosenfeld, A. Roy, L. Rushton, J.A. Salomon, U. Sampson, L. Sanchez-Riera, E. Sanman, A. Sapkota, S. Seedat, P. Shi, K. Shield, R. Shivakoti, G.M. Singh, D.A. Sleet, E. Smith, K.R. Smith, N.J.C. Stapelberg, K. Steenland, H. Stöckl, L.J. Stovner, K. Straif, L. Straney, G.D. Thurston, J.H. Tran, R. Van Dingenen, A. van Donkelaar, J.L. Veerman, L. Vijayakumar, R. Weintraub, M.M. Weissman, R.A. White, H. Whiteford, S.T. Wiersma, J.D. Wilkinson, H.C. Williams, W. Williams, N. Wilson, A.D. Woolf, P. Yip, J.M. Zielinski, A.D. Lopez, C.J.L. Murray, and M. Ezzati, 2012: A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010. *Lancet*, **380(9859)**, 2224-2260.

Lin, R.T. and C.C. Chan, 2009: Effects of heat on workers' health and productivity in Taiwan. *Global Health Action*, **2**, doi: 10.3402/gha.v2i0.2024.

Lindgren, E. and R. Gustafson, 2001: Tick-borne encephalitis in Sweden and climate change. *Lancet*, **358(9275)**, 16-18.

Liu, C., N. Hofstra, and E. Franz, 2013a: Impacts of climate change on the microbial safety of pre-harvest leafy green vegetables as indicated by *Escherichia coli* O157 and *Salmonella* spp. *International Journal of Food Microbiology*, **163(2-3)**, 119-128.

Liu, Q., X. Liu, Cirendunzhu, A. Woodward, Pengcuociren, L. Bai, Baimaciwang, S. Sang, Dazhen, F. Wan, L. Zhou, Y. Guo, H. Wu, G. Li, L. Lu, J. Wang, Dawa, C. Chu, and Xiraoruodeng, 2013b: Mosquitoes established in Lhasa city, Tibet, China. *Parasites and Vectors*, **6**, 224, doi:10.1186/1756-3305-6-2241-10.

Liu, X., B. Jiang, W. Gu, and Q. Liu, 2011: Temporal trend and climate factors of hemorrhagic fever with renal syndrome epidemic in Shenyang City, China. *BMC Infectious Diseases*, **11**, 331, doi:10.1186/1471-2334-11-331.

Lloyd, S.J., R.S. Kovats, and Z. Chalabi, 2011: Climate change, crop yields, and malnutrition: development of a model to quantify the impact of climate scenarios on child malnutrition. *Environmental Health Perspectives*, **119(12)**, 1817-1823.

Lobell, D.B., W. Schlenker, and J. Costa-Roberts, 2011a: Climate trends and global crop production since 1980. *Science*, **333(6042)**, 616-620.

Lobell, D.B., M. Bänziger, C. Magorokosho, and B. Vivek, 2011b: Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature Climate Change*, **1(1)**, 42-45.

Lockwood, A.H., 2012: *The Silent Epidemic: Coal and the Hidden Threat to Health.* MIT Press, Cambridge, MA, USA, 248 pp.

Lowe, D., K.L. Ebi, and B. Forsberg, 2011: Heatwave early warning systems and adaptation advice to reduce human health consequences of heatwaves. *International Journal of Environmental Research and Public Health*, **8(12)**, 4623-4648.

Lozano-Fuentes, S., M.H. Hayden, C. Welsh-Rodriguez, C. Ochoa-Martinez, B. Tapia-Santos, K.C. Kobylinski, C.K. Uejio, E. Zielinski-Gutierrez, L.D. Monache, A.J. Monaghan, D.F. Steinhoff, and L. Eisen, 2012: The dengue virus mosquito vector *Aedes aegypti* at high elevation in Mexico. *The American Journal of Tropical Medicine and Hygiene*, **87(5)**, 902-909.

Lu, L. and H. Lin, 2009: Time series analysis of dengue fever and weather in Guangzhou, China. *BMC Public Health*, **9**, 395, doi:10.1186/1471-2458-9-395.

Luber, G. and M. McGeehin, 2008: Climate change and extreme heat events. *American Journal of Preventive Medicine*, **35(5)**, 429-435.

Lucas, R.M., P. Valery, I. van der Mei, T. Dwyer, M.P. Pender, B. Taylor, A.-L. Ponsonby, and The Ausimmune Investigator Group, 2013: Sun exposure over a lifetime in Australian adults from latitudinally diverse regions. *Photochemistry & Photobiology*, **89(3)**, 737-744.

Luginbuhl, R., L. Jackson, D. Castillo, and K. Loringer, 2008: Heat-related deaths among crop workers – United States, 1992 - 2006. *JAMA: The Journal of the American Medical Association*, **300(9)**, 1017-1018, doi:10.1001/jama.300.9.1017.

Lukan, M., E. Bullova, and B. Petko, 2010: Climate warming and tick-borne encephalitis, Slovakia. *Emerging Infectious Diseases*, **16(3)**, 524-526.

Lunde, T.M., M.N. Bayoh, and B. Lindtjorn, 2013: How malaria models relate temperature to malaria transmission. *Parasites & Vectors*, **6**, 20, doi:10.1186/1756-3305-6-20.

Lutsey, P.L., M.A. Pereira, A.G. Bertoni, N.R. Kandula, and D.R. Jacobs, 2010: Interactions between race/ethnicity and anthropometry in risk of incident diabetes. *American Journal of Epidemiology*, **172(2)**, 197-204.

Lutz, W., W. Sanderson, and S. Scherbov, 2008: The coming acceleration of global population ageing. *Nature*, **451(7179)**, 716-719.

Lyons, C.L., M. Coetzee, J.S. Terblanche, and S.L. Chown, 2012: Thermal limits of wild and laboratory strains of two African malaria vector species, *Anopheles arabiensis* and *Anopheles funestus*. *Malaria Journal*, **11(1)**, 226, doi:10.1186/1475-2875-11-226.

Maas, J., R.A. Verheij, S. de Vries, P. Spreeuwenberg, F.G. Schellevis, and P.P. Groenewegen, 2009: Morbidity is related to a green living environment. *Journal of Epidemiology & Community Health*, **63(12)**, 967-973.

Macdonald, W.W., 1956: *Aedes aegypti* in Malaysia. II. Larval and adult biology. *Annals of Tropical Medicine and Parasitology*, **50(4)**, 399-414.

MacMillan, K., A.J. Monaghan, T. Apangu, K.S. Griffith, P.S. Mead, S. Acayo, R. Acidri, S.M. Moore, J.T. Mpanga, R.E. Enscore, K.L. Gage, and R.J. Eisen, 2012: Climate predictors of the spatial distribution of human plague cases in the West Nile Region of Uganda. *The American Journal of Tropical Medicine and Hygiene*, **86(3)**, 514-523.

Malik, S.M., H. Awan, and N. Khan, 2012: Mapping vulnerability to climate change and its repercussions on human health in Pakistan. *Globalization and Health*, **8**, 31, doi:10.1186/1744-8603-8-31.

Mallick, D.L., A. Rahman, M. Alam, A.S.M. Juel, A.N. Ahmad, and S.S. Alam, 2005: *Case Study 3: Bangladesh* Floods in Bangladesh: a shift from disaster management towards disaster preparedness. *IDS Bulletin*, **36(4)**, 53-70.

Maloney, S. and C. Forbes, 2011: What effect will a few degrees of climate change have on human heat balance? Implications for human activity. *International Journal of Biometeorology*, **55(2)**, 147-160.

Mangal, T.D., S. Paterson, and A. Fenton, 2008: Predicting the impact of long-term temperature changes on the epidemiology and control of schistosomiasis: a mechanistic model. *PLoS One*, **3(1)**, e1438, doi:10.1371/journal.pone.0001438.

Markandya, A., B.G. Armstrong, S. Hales, A. Chiabai, P. Criqui, S. Mima, C. Tonne, and P. Wilkinson, 2009: Public health benefits of strategies to reduce greenhouse-gas emissions: low-carbon electricity generation. *Lancet*, **374(9706)**, 2006-2015.

Marques, A., M.L. Nunes, S.K. Moore, and M.S. Strom, 2010: Climate change and seafood safety: human health implications. *Food Research International*, **43(7)**, 1766-1779.

Martin, D., B. Belanger, P. Gosselin, J. Brazeau, C. Furgal, and S. Dery, 2007: Drinking water and potential threats to human health in Nunavik: adaptation strategies under climate change conditions. *Arctic*, **60(2)**, 195-202.

McCormack, G. and A. Shiell, 2011: In search of causality: a systematic review of the relationship between the built environment and physical activity among adults. *International Journal of Behavioral Nutrition and Physical Activity*, **8(1)**, 125, doi:10.1186/1479-5868-8-125.

McCracken, J.P., K.R. Smith, A. Diaz, M.A. Mittleman, and J. Schwartz, 2007: Chimney stove intervention to reduce long-term wood smoke exposure lowers blood pressure among Guatemalan women. *Environmental Health Perspectives*, **115(7)**, 996-1001.

McDonald, R.I., P. Green, D. Balk, B.M. Fekete, C. Revenga, M. Todd, and M. Montgomery, 2011: Urban growth, climate change and freshwater availability. *Proceedings of the National Academy of Sciences of the United States of America*, **108(15)**, 6312-6317.

McMichael, A.J., 2013a: Human health. In: *Four Degrees of Global Warming: Australia in a Hot World* [Christoff, P. (ed.)]. Routledge, Abingdon, UK and New York, NY, USA, 268 pp.

McMichael, A.J., 2013b: Globalization, climate change, and human health. *New England Journal of Medicine*, **368(14)**, 1335-1343.

McMichael, A.J., J.W. Powles, C.D. Butler, and R. Uauy, 2007: Food, livestock production, energy, climate change, and health. *Lancet*, **370(9594)**, 1253-1263.

McMichael, A.J., P. Wilkinson, R.S. Kovats, S. Pattenden, S. Hajat, B. Armstrong, N. Vajanapoom, E.M. Niciu, H. Mahomed, C. Kingkeow, M. Kosnik, M.S. O'Neill, I. Romieu, M. Ramirez-Aguilar, M.L. Barreto, N. Gouveia, and B. Nikiforov, 2008: International study of temperature, heat and urban mortality: the ISOTHURM project. *International Journal of Epidemiology*, **37(5)**, 1121-1131.

McMichael, C., J. Barnett, and A.J. McMichael, 2012: An ill wind? Climate change, migration, and health. *Environmental Health Perspectives*, **120(5)**, 646-654.

Medlock, J.M. and A. Vaux, 2011: Assessing the possible implications of wetland expansion and management on mosquitoes in Britain. *European Mosquito Bulletin*, **29**, 38-65.

Meister, K., C. Johansson, and B. Forsberg, 2012: Estimated short-term effects of coarse particles on daily mortality in Stockholm, Sweden. *Environmental Health Perspectives*, **120(3)**, 431-436.

Michon, P., J.L. Cole-Tobian, and E. Dabod, S. Schoepflin, J. Igu, M. Susapu, N. Tarongka, P.A. Zimmerman, J.C. Reeder, J.G. Beeson, L. Schofield, C.L. King, and I. Mueller, 2007: The risk of malarial infections and disease in Papua New Guinean children. *The American Journal of Tropical Medicine and Hygiene*, **76(6)**, 997-1008.

Milojevic, A., B. Armstrong, S. Kovats, B. Butler, E. Hayes, G. Leonardi, V. Murray, and P. Wilkinson, 2011: Long-term effects of flooding on mortality in England and Wales, 1994-2005: controlled interrupted time-series analysis. *Environmental Health*, **10**, 11, doi:10.1186/1476-069X-10-11.

Milojevic, A., B. Armstrong, M. Hashizume, K. McAllister, A. Faruque, M. Yunus, P. Kim Streatfield, K. Moji, and P. Wilkinson, 2012: Health effects of flooding in rural Bangladesh. *Epidemiology*, **23(1)**, 107-115.

Mitchell, R. and F. Popham, 2007: Greenspace, urbanity and health: relationships in England. *Journal of Epidemiology & Community Health*, **61(8)**, 681-683.

Moore, S.K., N.J. Mantua, and E.P. Salathé Jr., 2011: Past trends and future scenarios for environmental conditions favoring the accumulation of paralytic shellfish toxins in Puget Sound shellfish. *Harmful Algae*, **10(5)**, 521-529.

Morabito, M., F. Profili, A. Crisci, P. Francesconi, G. Gensini, and S. Orlandini, 2012: Heat-related mortality in the Florentine area (Italy) before and after the exceptional 2003 heat wave in Europe: an improved public health response? *International Journal of Biometeorology*, **56(5)**, 801-810.

Morello-Frosch, R., M. Zuk, M. Jerrett, B. Shamasunder, and A.D. Kyle, 2011: Understanding the cumulative impacts of inequalities in environmental health: implications for policy. *Health Affairs*, **30(5)**, 879-887.

Murray, C.J.L., L.C. Rosenfeld, S.S. Lim, K.G. Andrews, K.J. Foreman, D. Haring, N. Fullman, M. Naghavi, R. Lozano, and A.D. Lopez, 2012: Global malaria mortality between 1980 and 2010: a systematic analysis. *Lancet*, **379(9814)**, 413-431.

Nakazawa, Y., R. Williams, A.T. Peterson, P. Mead, E. Staples, and K.L. Gage, 2007: Climate change effects on plague and tularemia in the United States. *Vector-Borne and Zoonotic Diseases*, **7(4)**, 529-540.

Neelormi, S., N. Adri, and A. Ahmed, 2009: Gender dimensions of differential health effects of climate change induced water-logging: a case study from coastal Bangladesh. *Proceedings of IOP Conference Series: Earth and Environmental Science*, **6**, 142026, doi:10.1088/1755-1307/6/14/142026.

Nelson, G.C., M.W. Rosegrant, A. Palazzo, I. Gray, C. Ingersoll, R. Robertson, S. Tokgov, T. Zhu, T.B. Sulser, C. Ringler, S. Msangi, and L. You, 2010: *Food Security, Farming and Climate Change to 2050. Scenarios, Results, Policy Options.* International Food Policy Research Institute (IFPRI), Washington, DC, USA, 131 pp.

Nelson, G.C., M.W. Rosegrant, J. Koo, R. Robertson, T. Sulser, T. Zhu, C. Ringler, S. Msangi, A. Palazzo, M. Batka, M. Magalhaes, R. Valmonte-Santos, M. Ewing, and D. Lee, 2009: *Climate Change: Impact on Agriculture and Costs of Adaptation.* International Food Policy Research Institute (IFPRI), Washington, DC, USA, 19 pp.

Nemet, G.F., T. Holloway, and P. Meier, 2010: Implications of incorporating air-quality co-benefits into climate change policymaking. *Environmental Research Letters*, **5(1)**, 014007, doi:10.1088/1748-9326/5/1/014007.

Neria, Y., 2012: Mental health effects of Hurricane Sandy characteristics, potential aftermath, and response. *JAMA: The Journal of the American Medical Association*, **308(24)**, 2571- 2572, doi:10.1001/jama.2012.110700.

Nitschke, M., G. Tucker, A. Hansen, S. Williams, Y. Zhang, and B. Peng, 2011: Impact of two recent extreme heat episodes on morbidity and mortality in Adelaide, South Australia: a case-series analysis. *Environmental Health*, **10(1)**, 42-51.

Nunn, P.D., 2009: Responding to the challenges of climate change in the Pacific Islands: management and technological imperatives. *Climate Research*, **40**, 211-231.

O'Brien, K., M. Pelling, A. Patwardhan, S. Hallegatte, A. Maskrey, T. Oki, U. Oswald-Spring, T. Wilbanks, and P.Z. Yanda, 2012: Toward a sustainable and resilient future. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 437-486.

OECD, 2012: *OECD Environmental Outlook to 2050: The Consequences of Inaction.* Organisation for Economic Co-operation and Development (OECD), OECD Publishing, Paris, France, 349 pp.

Ogden, N.H., A. Maarouf, I.K. Barker, M. Bigras-Poulin, L.R. Lindsay, M.G. Morshed, C.J. O'callaghan, F. Ramay, D. Waltner-Toews, and D.F. Charron, 2006: Climate change and the potential for range expansion of the Lyme disease vector *Ixodes scapularis* in Canada. *International Journal for Parasitology*, **36(1)**, 63-70.

Ogden, N.H., L. St-Onge, I.K. Barker, S. Brazeau, M. Bigras-Poulin, D.F. Charron, C.M. Francis, A. Heagy, L.R. Lindsay, A. Maarouf, P. Michel, F. Milord, C.J. O'Callaghan, L. Trudel, and R.A. Thompson, 2008: Risk maps for range expansion of the Lyme disease vector, *Ixodes scapularis*, in Canada now and with climate change. *International Journal of Health Geographics*, **7**, 24, doi:10.1186/1476-072X-7-24.

Ogden, N.H., C. Bounchard, K. Kurtenbach, G. Margos, L.R. Lindsay, L. Trudel, S. Nguon, and F. Milord, 2010: Active and passive surveillance and phylogenetic analysis of *Borrelia burgdorferi* elucidate the process of Lyme disease risk emergence in Canada. *Environmental Health Perspectives*, **118(7)**, 909-914.

Oikonomou, E. and P. Wilkinson, 2012: Modelling the relative importance of the urban heat island and the thermal quality of dwellings for overheating in London. *Building and Environment*, **57**, 223-238.

Okuthe, O.S. and G.E. Buyu, 2006: Prevalence and incidence of tick-borne diseases in smallholder farming systems in the western-Kenya highlands. *Veterinary Parasitology*, **141(3-4)**, 307-312.

Omumbo, J., B. Lyon, S. Waweru, S. Connor, and M. Thomson, 2011: Raised temperatures over the Kericho tea estates: revisiting the climate in the East African highlands malaria debate. *Malaria Journal*, **10(12)**, doi:10.1186/1475-2875-10-12.

O'Neill, B., B. Liddle, L. Jiang, K.R. Smith, S. Pachauri, M. Dalton, and R. Fuchs, 2012: Demographic change and CO_2 emissions. *Lancet*, **380(9837)**, 157-164.

Ostro, B., S. Rauch, R. Green, B. Malig, and R. Basu, 2010: The effects of temperature and use of air conditioning on hospitalizations. *American Journal of Epidemiology*, **172(9)**, 1053-1061.

Paaijmans, K.P., A.F. Read, and M.B. Thomas, 2009: Understanding the link between malaria risk and climate. *Proceedings of the National Academy of Sciences of the United States of America*, **106(33)**, 13844-13849.

Paaijmans, K.P., S. Blanford, A.S. Bell, J.I. Blanford, A.F. Read, and M.B. Thomas, 2010: Influence of climate on malaria transmission depends on daily temperature variation. *Proceedings of the National Academy of Sciences of the United States of America*, **107(34)**, 15135-15139.

Padmanabha, H., E. Soto, M. Mosquera, C.C. Lord, and L.P. Lounibos, 2010: Ecological links between water storage behaviors and *Aedes aegypti* production: implications for dengue vector control in variable climates. *Ecohealth*, **7(1)**, 78-90.

Paerl, H.W., N.S. Hall, and E.S. Calandrino, 2011: Controlling harmful cyanobacterial blooms in a world experiencing anthropogenic and climatic-induced change. *Science of the Total Environment*, **409(10)**, 1739-1745.

Page, L.A., S. Hajat, and R.S. Kovats, 2007: Relationship between daily suicide counts and temperature in England and Wales. *The British Journal of Psychiatry: The Journal of Mental Science*, **191**, 106-112.

Palecki, M.A., S.A. Changnon, and K.E. Kunke, 2001: The nature and impacts of the July 1999 heat wave in the midwestern United States: learning from the lessons of 1995. *Bulletin of the American Meteorological Society*, **82(7)**, 1353-1367.

Pan, A., Q. Sun, A.M. Bernstein, M.B. Schulze, J.E. Manson, M.J. Stampfer, W.C. Willett, and F.B. Hu, 2012: Red meat consumption and mortality: results from 2 prospective cohort studies. *Archives of Internal Medicine*, **172(7)**, 555-563.

Pandey, K., 2010: *Costs of Adapting to Climate Change for Human Health in Developing Countries.* Discussion Paper No. 11, Economics of Adaptation to Climate Change (EACC) study, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 19 pp.

Paranjothy, S., J. Gallacher, R. Amlot, G.J. Rubin, L. Page, T. Baxter, J. Wight, D. Kirrage, R. McNaught, and P. SR, 2011: Psychosocial impact of the summer 2007 floods in England. *BMC Public Health*, **11(1)**, 145, doi:10.1186/1471-2458-11-145.

Parsons, K.C., 2003: *Human Thermal Environments: The Effects of Hot, Moderate, and Cold Environments on Human Health, Comfort, and Performance.* 2nd edn., Taylor & Francis, London, UK and New York, NY, USA, 527 pp.

Pascual, M., J.A. Ahumada, L.F. Chaves, X. Rodo, and M. Bouma, 2006: Malaria resurgence in the East African highlands: temperature trends revisited. *Proceedings of the National Academy of Sciences of the United States of America*, **103(15)**, 5829-5834.

Patt, A.G., M. Tadross, P. Nussbaumer, K. Asante, M. Metzger, J. Rafael, A. Goujon, and G. Brundrit, 2010: Estimating least-developed countries' vulnerability to climate-related extreme events over the next 50 years. *Proceedings of the National Academy of Sciences of the United States of America*, **107(4)**, 1333-1337.

Patz, J.A., S.J. Vavrus, C.K. Uejio, and S.L. McLellan, 2008: Climate change and waterborne disease risk in the Great Lakes region of the U.S. *American Journal of Preventive Medicine*, **35(5)**, 451-458.

Paz, S., 2009: Impact of temperature variability on cholera incidence in Southeastern Africa, 1971-2006. *Ecohealth*, **6(3)**, 340-345.

Pearce, T., J. Ford, F. Duerden, B. Smit, M. Andrachuk, L. Berrang-Ford, and T. Smith, 2011: Advancing adaptation planning for climate change in the Inuvialuit Settlement Region (ISR): a review and critique. *Regional Environmental Change*, **11(1)**, 1-17.

Peduzzi, P., B. Chatenoux, H. Dao, A. De Bono, C. Herold, J. Kossin, F. Mouton, and O. Nordbeck, 2012: Global trends in tropical cyclone risk. *Nature Climate Change*, **2(4)**, 289-294.

Peng, R.D., J.F. Bobb, C. Tebaldi, L. McDaniel, M.L. Bell, and F. Dominici, 2011: Toward a quantitative estimate of future heat wave mortality under global climate change. *Environmental Health Perspectives*, **119(5)**, 701-706.

Perera, F.P., 2008: Children are likely to suffer most from our fossil fuel addiction. *Environmental Health Perspectives*, **116(8)**, 987-990.

Pettersson, L., J. Boman, P. Juto, M. Evander, and C. Ahlm, 2008: Outbreak of Puumala virus infection, Sweden. *Emerging Infectious Diseases*, **14(5)**, 808-810.

Pham, H.V., H.T. Doan, T.T. Phan, and N.N. Minh, 2011: Ecological factors associated with dengue fever in a Central Highlands province, Vietnam. *BMC Infectious Diseases*, **11**, 172, doi:10.1186/1471-2334-11-172.

Piesse, J. and C. Thirtle, 2009: Three bubbles and a panic: an explanatory review of recent food commodity price events. *Food Policy*, **34**, 119-129.

Pitzer, V.E., C. Viboud, L. Simonsen, C. Steiner, C.A. Panozzo, W.J. Alonso, M.A. Miller, R.I. Glass, J.W. Glasser, U.D. Parashar, and B.T. Grenfell, 2009: Demographic variability, vaccination, and the spatiotemporal dynamics of rotavirus epidemics. *Science*, **325(5938)**, 290-294.

Pitzer, V.E., C. Viboud, B.A. Lopman, M.M. Patel, U.D. Parashar, and B.T. Grenfell, 2011: Influence of birth rates and transmission rates on the global seasonality of rotavirus incidence. *Journal of the Royal Society Interface*, **8(64)**, 1584-1593.

Po, J.Y., J.M. FitzGerald, and C. Carlsten, 2011: Respiratory disease associated with solid biomass fuel exposure in rural women and children: systematic review and meta-analysis. *Thorax*, **66(3)**, 232-239.

Pokhrel, A.K., M.N. Bates, S.C. Verma, H.S. Joshi, C.T. Sreeramareddy, and K.R. Smith, 2010: Tuberculosis and indoor biomass and kerosene use in Nepal: a case-control study. *Environmental Health Perspectives*, **118(4)**, 558-564.

Polvani, L.M., D.W. Waugh, G.J.P. Correa, and S.W. Son, 2011: Stratospheric ozone depletion: the main driver of twentieth-century atmospheric circulation changes in the Southern Hemisphere. *Journal of Climate*, **24(3)**, 795-812.

Porter, J.R. and M. Gawith, 1999: Temperatures and the growth and development of wheat: a review. *European Journal of Agronomy*, **10(1)**, 23-36.

Porter, J.R. and M.A. Semenov, 2005: Crop responses to climatic variation. *Philosophical Transactions of the Royal Society B*, **360(1463)**, 2021-2035.

Potts, M. and C.E. Henderson, 2012: Global warming and reproductive health. *International Journal of Gynecology & Obstetrics*, **119**, 564-567.

Prata, N., 2009: Making family planning accessible in resource-poor settings. *Philosophical Transactions of the Royal Society B*, **364(1532)**, 3093-3099.

PricewaterhouseCoopers, 2012: *Too Late for Two Degrees? Low Carbon Economy Index 2012.* PricewaterhouseCoopers (PwC) LLP, London, UK, 13 pp.

Pudpong, N. and S. Hajat, 2011: High temperature effects on out-patient visits and hospital admissions in Chiang Mai, Thailand. *Science of the Total Environment*, **409(24)**, 5260-5267.

Puppim de Oliveira, J.A., 2009: The implementation of climate change related policies at the subnational level: an analysis of three countries. *Habitat International*, **33(3)**, 253-259.

Raffel, T.R., J.M. Romansic, N.T. Halstead, T.A. McMahon, M.D. Venesky, and J.R. Rohr, 2012: Disease and thermal acclimation in a more variable and unpredictable climate. *Nature Climate Change*, **3(2)**, 146-151.

Ramanathan, V. and G. Carmichael, 2008: Global and regional climate changes due to black carbon. *Nature Geoscience*, **1(4)**, 221-227.

Ramin, B.M. and A.J. McMichael, 2009: Climate change and health in sub-Saharan Africa: a case-based perspective. *Ecohealth*, **6(1)**, 52-57.

Ramsey, J.D., 1995: Task performance in heat: a review. *Ergonomics*, **38(1)**, 154-165.

Ramsey, J.D. and T.E. Bernard, 2000: Heat stress. In: *Patty´s Industrial Hygiene, Fifth Edition* [Harris, R.L. (ed.)]. John Wiley and Sons, New York, NY, USA, pp. 925-985.

Randolph, S.E., 2010: To what extent has climate change contributed to the recent epidemiology of tick-borne diseases? *Veterinary Parasitology*, **167(2-4)**, 92-94.

Ranjit, S. and N. Kissoon, 2011: Dengue hemorrhagic fever and shock syndromes. *Pediatric Critical Care Medicine*, **12(1)**, 90-100.

Reed, J. and B. Ainsworth, 2007: Perceptions of environmental supports on the physical activity behaviors of university men and women: a preliminary investigation. *The Journal of American College Health*, **56(2)**, 199-204.

Reid, C.E., M.S. O'Neill, C.J. Gronlund, S.J. Brines, D.G. Brown, A.V. Diez-Roux, and J. Schwartz, 2009: Mapping community determinants of heat vulnerability. *Environmental Health Perspectives*, **117(11)**, 1730-1736.

Ren, C., G.M. Williams, L. Morawska, K. Mengersen, and S. Tong, 2008: Ozone modifies associations between temperature and cardiovascular mortality: analysis of the NMMAPS data. *Occupational and Environmental Medicine*, **65(4)**, 255-260.

Reyburn, R., D.R. Kim, M. Emch, A. Khatib, L. von Seidlein, and M. Ali, 2011: Climate variability and the outbreaks of cholera in Zanzibar, East Africa: a time series analysis. *The American Journal of Tropical Medicine and Hygiene*, **84(6)**, 862-869.

Rinaldo, A., E. Bertuzzo, L. Mari, L. Righetto, M. Blokesch, M. Gatto, R. Casagrandi, M. Murray, S.M. Vesenbeckh, and I. Rodriguez-Iturbe, 2012: Reassessment of the 2010-2011 Haiti cholera outbreak and rainfall-driven multiseason projections. *Proceedings of the National Academy of Sciences of the United States of America*, **109(17)**, 6602-6607.

Rive, N. and K. Aunan, 2010: Quantifying the air quality cobenefits of the clean development mechanism in China. *Environmental Science & Technology*, **44(11)**, 4368-4375.

Rocklov, J. and B. Forsberg, 2009: Comparing approaches for studying the effects of climate extremes – a case study of hospital admissions in Sweden during an extremely warm summer. *Global Health Action*, **2**, doi:10.3402/gha.v2i0.20341-11.

Rocklov, J., B. Forsberg, and K. Meister, 2009: Winter mortality modifies the heat-mortality association the following summer. *The European Respiratory Journal*, **33(2)**, 245-251.

Rocklov, J., K. Ebi, and B. Forsberg, 2011: Mortality related to temperature and persistent extreme temperatures: a study of cause-specific and age-stratified mortality. *Occupational and Environmental Medicine*, **68(7)**, 531-536.

Rogelj, J., B. Hare, J. Nabel, K. Macey, M. Schaeffer, K. Markmann, and M. Meinshausen, 2009: Halfway to Copenhagen, no way to 2 °C. *Nature Reports Climate Change*, **3(July 2009)**, 81-83, doi:10.1038/climate.2009.571.

Ronan, K.R., K. Crellin, D.M. Johnston, K. Finnis, D. Paton, and J. Becker, 2008: Promoting child and family resilience to disasters: effects, interventions and prevention effectiveness. *Children, Youth and Environments*, **18(1)**, 332-353.

Rundle, A., K.M. Neckerman, L. Freeman, G.S. Lovasi, M. Purciel, J. Quinn, C. Richards, N. Sircar, and C. Weiss, 2009: Neighborhood food environment and walkability predict obesity in New York City. *Environmental Health Perspectives*, **117(3)**, 442-447.

Russell, R.C., B.J. Currie, M.D. Lindsay, J.S. Mackenzie, S.A. Ritchie, and P.I. Whelan, 2009: Dengue and climate change in Australia: predictions for the future should incorporate knowledge from the past. *Medical Journal of Australia*, **190(5)**, 265-268.

Rutstein, S.O., 2005: Effects of preceding birth intervals on neonatal, infant and under-five years mortality and nutritional status in developing countries: evidence from the demographic and health surveys. *International Journal of Gynecology & Obstetrics*, **89(Suppl. 1)**, S7-S24.

Sahu, S., M. Sett, and T. Kjellstrom, 2013: Heat exposure, cardiovascular stress and work productivity in rice harvesters in India: implications for a climate change future. *Industrial Health*, **51(4)**, 424-431.

Salomon, J.A., H. Wang, M.K. Freeman, T. Vos, A.D. Flaxman, A.D. Lopez, and C.J. Murray, 2012: Healthy life expectancy for 187 countries, 1990-2010: a systematic analysis for the Global Burden Disease Study 2010. *Lancet*, **380(9859)**, 2144-2162.

Samson, J., D. Berteaux, B.J. McGill, and M.M. Humphries, 2011: Geographic disparities and moral hazards in the predicted impacts of climate change on human populations. *Global Ecology and Biogeography*, **20(4)**, 532-544.

Sankoh, O. and P. Byass, 2012: The INDEPTH Network: filling vital gaps in global epidemiology. *International Journal of Epidemiology*, **41(3)**, 579-588.

Satish, U., M.J. Mendell, K. Shekhar, T. Hotchi, D. Sullivan, S. Streufert, and W.J. Fisk, 2012: Is CO_2 an indoor pollutant? Direct effects of low-to-moderate CO_2 concentrations on human decision-making performance. *Environmental Health Perspectives*, **120(12)**, 1671-1677.

Sauerborn, R. and K. Ebi, 2012: Climate change and natural disasters – integrating science and practice to protect health. *Global Health Action*, **5**, 19295, doi: 10.3402/gha.v5i0.19295.

Schlenker, W. and M.J. Roberts, 2009: Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **106(37)**, 15594-15598.

Schmier, J.K. and K.L. Ebi, 2009: The impact of climate change and aeroallergens on children's health. *Allergy and Asthma Proceedings*, **30(3)**, 229-237.

Schnitzler, J., J. Benzler, D. Altmann, I. Muecke, and G. Krause, 2007: Survey on the population's needs and the public health response during floods in Germany 2002. *Journal of Public Health Management and Practice*, **13(5)**, 461-464.

Schulte, P.A. and H. Chun, 2009: Climate change and occupational safety and health: establishing a preliminary framework. *Journal of Occupational & Environmental Hygiene*, **6(9)**, 542-554.

Selin, N.E., S. Wu, K.M. Nam, J.M. Reilly, S. Paltsev, R.G. Prinn, and M.D. Webster, 2009: Global health and economic impacts of future ozone pollution. *Environmental Research Letters*, **4**, 044014, doi:10.1088/1748-9326/4/4/044014.

Sheffield, P.E., K. Knowlton, J.L. Carr, and P.L. Kinney, 2011: Modeling of regional climate change effects on ground-level ozone and childhood asthma. *American Journal of Preventive Medicine*, **41(3)**, 251-257 and quiz A3, doi: 10.1016/j.amepre.2011.04.017.

Sherry, R.A., X. Zhou, S. Gu, J.A. Arnone, D.S. Schimel, P.S. Verburg, L.L. Wallace, and Y. Luo, 2007: Divergence of reproductive phenology under climate warming. *Proceedings of the National Academy of Sciences of the United States of America*, **104(1)**, 198-202.

Sherwood, S.C. and M. Huber, 2010: An adaptability limit to climate change due to heat stress. *Proceedings of the National Academy of Sciences of the United States of America*, **107(21)**, 9552-9555.

Shindell, D., J.C.I. Kuylenstierna, E. Vignati, R. van Dingenen, M. Amann, Z. Klimont, S.C. Anenberg, N. Muller, G. Janssens-Maenhout, F. Raes, J. Schwartz, G. Faluvegi, L. Pozzoli, K. Kupiainen, L. Höglund-Isaksson, L. Emberson, D. Streets, V. Ramanathan, K. Hicks, N.T.K. Oanh, G. Milly, M. Williams, V. Demkine, and D. Fowler, 2012: Simultaneously mitigating near-term climate change and improving human health and food security. *Science*, **335(6065)**, 183-189.

Shonkoff, S., R. Morello-Frosch, M. Pastor, and J. Sadd, 2011: Environmental health and equity implications of climate change and mitigation policies in California: a review of the literature. *Climatic Change*, **109(Suppl. 1)**, S485-S503.

Silva, H.R., P.E. Phelan, and J.S. Golden, 2010: Modeling effects of urban heat island mitigation strategies on heat-related morbidity: a case study for Phoenix, Arizona, USA. *International Journal of Biometeorology*, **54(1)**, 13-22.

Sinha, R., A.J. Cross, B.I. Graubard, M.F. Leitzmann, and A. Schatzkin, 2009: Meat intake and mortality: a prospective study of over half a million people. *Archives of Internal Medicine*, **169(6)**, 562-571.

Smith, K.R., 2008: Comparative environmental health assessments. *Annals of the New York Academy of Sciences*, **1140**, 31-39.

Smith, K.R. and K. Balakrishnan, 2009: Mitigating climate, meeting MDGs, and moderating chronic disease: the health co-benefits landscape. In: *Commonwealth Health Ministers' Update 2009* [Commonwealth Secretariat (ed.)]. Commonwealth Secretariat, London, UK, pp. 59-65.

Smith, K.R. and E. Haigler, 2008: Co-benefits of climate mitigation and health protection in energy systems: scoping methods. *Annual Review of Public Health*, **29**, 11-25.

Smith, K.R., M. Jerrett, H.R. Anderson, R.T. Burnett, V. Stone, R. Derwent, R.W. Atkinson, A. Cohen, S.B. Shonkoff, D. Krewski, C.A. Pope III, M.J. Thun, and G. Thurston, 2009: Public health benefits of strategies to reduce greenhouse-gas emissions: health implications of short-lived greenhouse pollutants. *Lancet*, **374(9707)**, 2091-2103.

Smith, K.R., J.P. McCracken, M.W. Weber, A. Hubbard, A. Jenny, L.M. Thompson, J. Balmes, A. Diaz, B. Arana, and N. Bruce, 2011: Effect of reduction in household air pollution on childhood pneumonia in Guatemala (RESPIRE): a randomised controlled trial. *The Lancet*, **378(9804)**, 1717-1726.

Smith, K.R., H. Frumkin, K. Balakrishnan, C.D. Butler, Z.A. Chafe, I. Fairlie, P. Kinney, T. Kjellstrom, D.L. Mauzerall, T.E. McKone, A.J. McMichael, and M. Schneider, 2013: Energy and human health. *Annual Review of Public Health*, **34**, 159-188.

Sokolnicki, L.A., N.A. Strom, S.K. Roberts, S.A. Kingsley-Berg, A. Basu, and N. Charkoudian, 2009: Skin blood flow and nitric oxide during body heating in type 2 diabetes mellitus. *Journal of Applied Physiology*, **106(2)**, 566-570.

Sousa, C.A., M. Clairouin, G. Seixas, B. Viveiros, M.T. Novo, A.C. Silva, M.T. Escoval, and A. Economopoulou, 2012: Ongoing outbreak of dengue type 1 in the Autonomous Region of Madeira, Portugal: preliminary report. *Eurosurveillance*, **17(49)**, 20333, www.eurosurveillance.org/ViewArticle.aspx?ArticleId=20333.

Stafoggia, M., F. Forastiere, P. Michelozzi, and C.A. Perucci, 2009: Summer temperature-related mortality: effect modification by previous winter mortality. *Epidemiology*, **20(4)**, 575-583.

Stanke, C., M. Kerac, C. Prudhomme, J. Medlock, and V. Murray, 2013: Health effects of drought: a systematic review of the evidence. *PLOS Current Disasters*, June 5, **Edition 1**, doi:10.1371/currents.dis.7a2cee9e980f91ad7697b570bcc4b0041.

State Environmental Institution "Mosecomonitoring", 2010: Air quality monitoring in Moscow. *WHO Collaborating Centre for Air Quality Management and Air Pollution Control Newsletter*, **(46)**, 9-14.

Stenseth, N.C., N.I. Samia, H. Viljugrein, K.L. Kausrud, M. Begon, S. Davis, H. Leirs, V.M. Dubyanskiy, J. Esper, V.S. Ageyev, N.L. Klassovskiy, S.B. Pole, and K.S. Chan, 2006: Plague dynamics are driven by climate variation. *Proceedings of the National Academy of Sciences of the United States of America*, **103(35)**, 13110-13115.

Stern, D.I., P.W. Gething, C.W. Kabaria, W.H. Temperley, A.M. Noor, E.A. Okiro, G.D. Shanks, R.W. Snow, and S.I. Hay, 2011: Temperature and malaria trends in highland East Africa. *PLoS One*, **6(9)**, e24524, doi:10.1371/journal.pone.0024524.

Stone, B., J.J. Hess, and H. Frumkin, 2010: Urban form and extreme heat events: are sprawling cities more vulnerable to climate change than compact cities? *Environmental Health Perspectives*, **118(10)**, 1425-1428.

Strand, L.B., A.G. Barnett, and S. Tong, 2012: Maternal exposure to ambient temperature and the risks of preterm birth and stillbirth in Brisbane, Australia. *American Journal of Epidemiology*, **175(2)**, 99-107.

Suárez-Varela, M., L. Garcia-Marcos Alvarez, M. Kogan, A. González, A. Gimeno, I. Ontoso, C. Diaz, A. Pena, B. Aurrecoechea, R. Monge, A. Quiros, J. Garrido, I. Canflanca, and Á. Varela, 2008: Climate and prevalence of atopic eczema in 6- to 7-year-old school children in Spain. ISAAC PhASE III. *International Journal of Biometeorology*, **52(8)**, 833-840.

Sudre, B., M. Rossi, W. Van Bortel, K. Danis, A. Baka, and N. Vakalis, 2013: Mapping environmental suitability for malaria transmission, Greece. *Emerging Infectious Diseases*, **19(5)**, 784-786, doi:10.3201/eid1905.120811.

Sumilo, D., A. Bormane, L. Asokliene, V. Vasilenko, I. Golovljova, T. Avsic-Zupanc, Z. Hubalek, and S.E. Randolph, 2008: Socio-economic factors in the differential upsurge of tick-borne encephalitis in Central and Eastern Europe. *Reviews in Medical Virology*, **18(2)**, 81-95.

Tagaris, E., K.J. Liao, A.J. Delucia, L. Deck, P. Amar, and A.G. Russell, 2009: Potential impact of climate change on air pollution-related human health effects. *Environmental Science & Technology*, **43(13)**, 4979-4988.

Tan, J., Y. Zheng, G. Song, L.S. Kalkstein, A.J. Kalkstein, and X. Tang, 2007: Heat wave impacts on mortality in Shanghai, 1998 and 2003. *International Journal of Biometeorology*, **51(3)**, 193-200.

Tate, J.E., C.A. Panozzo, D.C. Payne, M.M. Patel, M.M. Cortese, A.L. Fowkes, and U.D. Parashar, 2009: Decline and changes in seasonality of US rotavirus activity after the introduction of a rotavirus vaccine. *Pediatrics*, **124(2)**, 465-471.

Tate, J.E., A.H. Burton, C. Boschi-Pinto, A.D. Steele, J. Duque, U.D. Parashar, and the WHO-coordinated Global Rotavirus Surveillance Network, 2012: 2008 estimate of worldwide rotavirus-associated mortality in children younger than 5 years before the introduction of universal rotavirus vaccination programmes: a systematic review and meta-analysis. *The Lancet Infectious Diseases*, **12(2)**, 136-141.

Teague, B., R. McLeod, and S. Pascoe, 2010: *2009 Victorian Bushfires Royal Commission Final Report: Summary.* Parliament of Victoria, 2009 Victorian Bushfires Royal Commission, Melbourne, Australia, 42 pp.

Teixeira, E.I., G. Fischer, and H. van Velthuizen, 2011: Global hot-spots of heat stress on agricultural crops due to climate change. *Agricultural and Forest Meteorology*, **170**, 206-215.

Thompson, A.A., L. Matamale, and S.D. Kharidza, 2012: Impact of climate change on children's health in Limpopo Province, South Africa. *International Journal of Environmental Research and Public Health*, **9**, 831-854.

Thomson, M.C., F.J. Doblas-Reyes, S.J. Mason, R. Hagedorn, S.J. Connor, T. Phindela, A.P. Morse, and T.N. Palmer, 2006: Malaria early warnings based on seasonal climate forecasts from multi-model ensembles. *Nature*, **439(7076)**, 576-579.

Thornton, P., P. Jones, T. Owiyo, R. Kruska, M. Herrero, O. V, S. Bhadwal, P. Kristjanson, A. Notenbaert, and N. Bekele, 2008: Climate change and poverty in Africa: mapping hotspots of vulnerability. *African Journal of Agriculture and Resource Economics*, **2(1)**, 24-44.

Tilman, D., R. Socolow, J.A. Foley, J. Hill, E. Larson, L. Lynd, S. Pacala, J. Reilly, T. Searchinger, C. Somerville, and R. Williams, 2009: Beneficial biofuels – the food, energy, and environment trilemma. *Science*, **325(5938)**, 270-271.

Tirado, M.C., R. Clarke, L.A. Jaykus, A. McQuatters-Gollop, and J.M. Frank, 2010: Climate change and food safety: A review. *Climate Change and Food Science*, **43(7)**, 1745-1765.

Tokarevich, N.K., A.A. Tronin, O.V. Blinova, R.V. Buzinov, V.P. Boltenkov, E.D. Yurasova, and J. Nurse, 2011: The impact of climate change on the expansion of *Ixodes persulcatus* habitat and the incidence of tick-borne encephalitis in the north of European Russia. *Global Health Action*, **4**, 8448, doi:10.3402/gha.v4i0.8448.

Tollefsen, P., K. Rypdal, A. Torvanger, and N. Rive, 2009: Air pollution policies in Europe: efficiency gains from integrating climate effects with damage costs to health and crops. *Environmental Science & Policy*, **12(7)**, 870-881.

Tsai, D.H., J.L. Wang, C.H. Wang, and C.C. Chan, 2008: A study of ground-level ozone pollution, ozone precursors and subtropical meteorological conditions in central Taiwan. *Journal of Environmental Monitoring*, **10(1)**, 109-118.

Tsui, A.O., A.A. Creanga, and S. Ahmed, 2007: The role of delayed childbearing in the prevention of obstetric fistulas. *International Journal of Gynecology & Obstetrics*, **99(Suppl. 1)**, S98-S107.

Turcios, R.M., A.T. Curns, R.C. Holman, I. Pandya-Smith, A. LaMonte, J.S. Bresee, R.I. Glass, and the National Respiratory and Enteric Virus Surveillance System Collaborating Laboratories, 2006: Temporal and geographic trends of rotavirus activity in the United States, 1997-2004. *The Pediatric Infectious Disease Journal*, **25(5)**, 451-454.

Uejio, C.K., O.V. Wilhelmi, J.S. Golden, D.M. Mills, S.P. Gulino, and J.P. Samenow, 2011: Intra-urban societal vulnerability to extreme heat: the role of heat exposure and the built environment, socioeconomics, and neighborhood stability. *Geographies of Care*, **17(2)**, 498-507.

Ujah, I.A., O.A. Aisien, J.T. Mutihir, D.J. Vanderjagt, R.H. Glew, and V.E. Uguru, 2005: Factors contributing to maternal mortality in north-central Nigeria: a seventeen-year review. *African Journal of Reproductive Health*, **9(3)**, 27-40.

UN-HABITAT, 2011: *Cities and Climate Change: Global Report on Human Settlements 2011.* United Nations Human Settlements Programme (UN-HABITAT), Earthscan, London, UK and Washington, DC, USA, 279 pp.

UNDP, 2011: *Human Development Report 2011. Sustainability and Equity: A Better Future for All.* United Nations Development Programme (UNDP), New York, NY, USA, 185 pp.

UNEP, 2011: *Integrated Assessment of Black Carbon and Tropospheric Ozone.* United Nations Environment Programme (UNEP) and World Meteorological Organization (WMO), UNEP, Nairobi, Kenya and WMO, Geneva, Switzerland, 249 pp.

UNISDR, 2011: *2011 Global Assessment Report on Disaster Risk Reduction: Revealing Risk, Redefining Development.* United Nations International Strategy for Disaster Reduction (UNISDR), United Nations Office for Disaster Risk Reduction, Geneva, Switzerland, 178 pp.

van den Berg, A.E., J. Maas, R.A. Verheij, and P.P. Groenewegen, 2010: Green space as a buffer between stressful life events and health. *Social Science & Medicine*, **70(8)**, 1203-1210.

van der Leun, J.C., R.D. Piacentini, and F.R. de Gruijl, 2008: Climate change and human skin cancer. *Photochemical & Photobiological Sciences*, **7(6)**, 730-733.

van Dillen, S.M.E., S. de Vries, P.P. Groenewegen, and P. Spreeuwenberg, 2011: Greenspace in urban neighbourhoods and residents' health: adding quality to quantity. *Journal of Epidemiology and Community Health*, **66(6)**, e8, doi:10.1136/jech.2009.104695.

Van Kerkhove, M.D., K.A.H. Vandemaele, V. Shinde, G. Jaramillo-Gutierrez, A. Koukounari, C.A. Donnelly, L.O. Carlino, R. Owen, B. Paterson, L. Pelletier, J. Vachon, C. Gonzalez, Y. Hongjie, F. Zijian, K.C. Shuk, A. Au, S. Buda, G. Krause, W. Haas, and I. Bonmarin, 2011: Risk factors for severe outcomes following 2009 influenza A (H1N1) infection: a global pooled analysis. *PLoS Medicine*, **8(7)**, doi:10.1371/journal.pmed.1001053 1-12.

Van Kleef, E., H. Bambrick, and S. Hales, 2010: The geographic distribution of dengue fever and the potential influence of global climate change. *TropIKA.net*, **1(1)**, journal.tropika.net/scielo.php?script=sci_arttext&pid=S2078-86062010005000001&lng=en.

Vedal, S. and S.J. Dutton, 2006: Wildfire air pollution and daily mortality in a large urban area. *Environmental Research*, **102(1)**, 29-35.

Venkataraman, C., A.D. Sagar, G. Habib, N. Lam, and K.R. Smith, 2010: The Indian national initiative for advanced biomass cookstoves: the benefits of clean combustion. **14(2)**, 63-72.

Vezzulli, L., I. Brettar, E. Pezzati, P.C. Reid, R.R. Colwell, M.G. Hofle, and C. Pruzzo, 2012: Long-term effects of ocean warming on the prokaryotic community: evidence from the vibrios. *ISME Journal: Multidisciplinary Journal of Microbial Ecology*, **6(1)**, 21-30.

Wang, H., L. Dwyer-Lindgren, K.T. Lofgren, J.K. Rajaratnam, J.R. Marcus, A. Levin-Rector, C.E. Levitz, A. Lopez, and C.J.L. Murray, 2012: Age-specific and sex-specific mortality in 187 countries, 1970-2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet, 380, 2071-2094.

Wang, X., R. Chen, X. Meng, F. Geng, C. Wang, and H. Kan, 2013: Associations between fine particle, coarse particle, black carbon and hospital visits in a Chinese city. *Science of the Total Environment*, **458-460**, 1-6, doi:10.1016/j.scitotenv.2013.04.008.

Weis, K.E., 2011: Vibrio illness in Florida, 1998-2007. *Epidemiology and Infection*, **139(4)**, 591-598.

Weisent, J., W. Seaver, A. Odoi, and B. Rohrbach, 2010: Comparison of three time-series models for predicting campylobacteriosis risk. *Epidemiology and Infection*, **138(6)**, 898-906.

Weisskopf, M.G., H.A. Anderson, S. Foldy, L.P. Hanrahan, K. Blair, and T.J. Török, 2002: Heat wave morbidity and mortality, Milwaukee, Wis, 1999 vs 1995: an improved response? *American Journal of Public Health*, **29(5)**, 830-833.

West, J.J., A.M. Fiore, V. Naik, L.W. Horowitz, M.D. Schwarzkopf, and D.L. Mauzerall, 2007a: Ozone air quality and radiative forcing consequences of changes in ozone precursor emissions. *Geophysical Research Letters*, **34(6)**, L06806, doi:10.1029/2006GL029173.

West, J.J., S. Szopa, and D.A. Hauglustaine, 2007b: Human mortality effects of future concentrations of tropospheric ozone. *Comptes Rendus de l'Academe des Sciences: Geoscience*, **339**, 775-783, doi: 10.1016/j.crte.2007.08.005.

West, J.J., A. Fiore, and L. Horowitz, 2012: Scenarios of methane emission reductions to 2030: abatement costs and co-benefits to ozone air quality and human mortality. *Climatic Change*, **114(3-4)**, 441-461.

West, J.J., S.J. Smith, R.A. Silva, V. Naik, Y. Zhang, Z. Adelman, M.M. Fry, S. Anenberg, L.W. Horowitz, and J. Lamarque, 2013: Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nature Climate Change*, **3(10)**, 885-889.

WHO, 2003: *WHO Guide to Cost-Effectiveness Analysis* [Tan-Torres Edejer, T., R. Baltussem, T. Adam, R. Hutubessy, A. Acharya, D.B. Evans, and C.J.L. Murray (eds.)]. World Health Organization (WHO), Geneva, Switzerland, 318 pp.

WHO, 2006: *WHO Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide: Global Update 2005.* World Health Organization (WHO), Regional Office for Europe, Copenhagen, Denmark, 484 pp.

WHO, 2008: *The Global Burden of Disease. 2004 Update.* World Health Organization (WHO), Geneva, Switzerland, 146 pp.

WHO, 2009a: *WHO Guide to Identifying the Economic Consequences of Disease and Injury.* Department of Health Systems Financing, Health Systems and Services, World Health Organization (WHO), Geneva, Switzerland, 132 pp.

WHO, 2009b: *Save Lives: Make Hospitals Safe in Emergencies.* WHO/HAC/WHD/2009.1, World Health Organization (WHO), Geneva, Switzerland, 29 pp.

WHO, 2010: *World Malaria Report 2010.* Global Malaria Programme, World Health Organization (WHO), Geneva, Switzerland, 204 pp.

WHO, 2011: *Gender, Climate Change and Health.* Public Health & Environment Department (PHE), Health Security & Environment Cluster (HSE), World Health Organization (WHO), Geneva, Switzerland, 36 pp.

WHO, 2012: *World Malaria Report 2012.* Global Malaria Programme, World Health Organization (WMO), Geneva, Switzerland, 249 pp.

WHO, 2013: *Impact of Dengue*. World Health Organization (WHO), Geneva, Switzerland, www.who.int/csr/disease/dengue/impact/en/.

WHO and WMO, 2012: *Atlas of Health and Climate* [Castonguay, S. (ed.)]. World Health Organization (WHO) and World Meteorological Organization (WMO), Geneva, Switzerland, 64 pp.

WHO Regional Office for Europe, 2009: *Improving Public Health Responses to Extreme Weather/Heat-Waves – EuroHEAT: Technical Summary.* World Health Organization (WHO) Regional Office for Europe, Copenhagen, Denmark, 60 pp.

WHO Regional Office for Europe, 2010: *WHO Guidelines for Indoor Air Quality: Selected Pollutants.* World Health Organization (WHO), Regional Office for Europe, Copenhagen, Denmark, 454 pp.

WHO Regional Office for Europe, 2013: *Climate Change and Health: A Tool to Estimate Health and Adaptation Costs.* World Health Organization (WHO) Regional Office for Europe, Copenhagen, Denmark, 45 pp.

Wilkinson, P., K.R. Smith, S. Beevers, C. Tonne, and T. Oreszczyn, 2007a: Energy, energy efficiency, and the built environment. *Lancet*, **370(9593)**, 1175-1187.

Wilkinson, P., K.R. Smith, M. Joffe, and A. Haines, 2007b: A global perspective on energy: health effects and injustices. *Lancet*, **370(9591)**, 965-978.

Wilkinson, P., K.R. Smith, M. Davies, H. Adair, B.G. Armstrong, M. Barrett, N. Bruce, A. Haines, I. Hamilton, T. Oreszczyn, I. Ridley, C. Tonne, and Z. Chalabi, 2009: Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. *The Lancet*, **374(9705)**, 1917-1929.

Willett, K.M. and S. Sherwood, 2012: Exceedance of heat index thresholds for 15 regions under a warming climate using the wet-bulb globe temperature. *International Journal of Climatology*, **32(2)**, 161-177.

Williams, A.P. and C. Funk, 2011: A westward extension of the warm pool leads to a westward extension of the Walker circulation, drying eastern Africa. *Climate Dynamics*, **37(11-12)**, 2417-2435.

Woodcock, J., P. Edwards, C. Tonne, B.G. Armstrong, O. Ashiru, D. Banister, S. Beevers, Z. Chalabi, Z. Chowdhury, A. Cohen, O.H. Franco, A. Haines, R. Hickman, G. Lindsay, I. Mittal, D. Mohan, G. Tiwari, A. Woodward, and I. Roberts, 2009: Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. *Lancet*, **374(9705)**, 1930-1943.

Woodcock, J., M. Givoni, and A.S. Morgan, 2013: Health impact modelling of active travel visions for England and Wales using an Integrated Transport and Health Impact Modelling Tool (ITHIM). *Plos One*, **8(1)**, e51462, doi:10.1371/journal.pone.0051462.

Woodward, A., G. Lindsay, and S. Singh, 2011: Adapting to climate change to sustain health. *WIREs Climate Change*, **2(2)**, 271-282.

World Bank, 2010: *World Development Report 2010: Development and Climate Change.* The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 417 pp.

Wu, F., Q. Liu, L. Lu, J. Wang, X. Song, and D. Ren, 2011: Distribution of *Aedes albopictus* (Diptera: Culicidae) in northwestern China. *Vector-Borne and Zoonotic Diseases*, **11(8)**, 1181-1186.

Wu, P.C., J.G. Lay, H.R. Guo, C.Y. Lin, S.C. Lung, and H.J. Su, 2009: Higher temperature and urbanization affect the spatial patterns of dengue fever transmission in subtropical Taiwan. *Science of the Total Environment*, **407(7)**, 2224-2233.

Wyndham, C.H., 1969: Adaptation to heat and cold. *Environmental Research*, **2(5)**, 442-469.

Xu, L., Q. Liu, L.C. Stige, T. Ben Ari, X. Fang, K.S. Chan, S. Wang, N.C. Stenseth, and Z. Zhang, 2011: Nonlinear effect of climate on plague during the third pandemic in China. *Proceedings of the National Academy of Sciences of the United States of America*, **108(25)**, 10214-10219.

Xu, X., E. Yu, X. Gao, N. Song, L. Liu, X. Wei, W. Zhang, and C. Fu, 2012: Red and processed meat intake and risk of colorectal adenomas: a meta-analysis of observational studies. *International Journal of Cancer*, **132(2)**, 437-448.

Yoshida, S., T. Satake, and D.S. Mackill, 1981: *High-Temperature Stress in Rice*. IRRI Research Paper Series No. 67, International Rice Research Institute (IRRI), Manila, Philippines, 15 pp.

Zanobetti, A., M.S. O'Neill, C.J. Gronlund, and J.D. Schwartz, 2012: Summer temperature variability and long-term survival among elderly people with chronic disease. *Proceedings of the National Academy of Sciences of the United States of America*, **10(17)**, 6608-6613.

Zhang, J. and K. Smith, 2007: Household air pollution from coal and biomass fuels in China: measurements, health impacts, and interventions. *Environmental Health Perspectives*, **115(6)**, 848-855.

Zhang, Y., P. Bi, and J.E. Hiller, 2010: Climate variations and Salmonella infection in Australian subtropical and tropical regions. *Science of the Total Environment*, **408(3)**, 524-530.

Zhou, S.S., F. Huang, J.J. Wang, S.S. Zhang, Y.P. Su, and L.H. Tang, 2010: Geographical, meteorological and vectorial factors related to malaria re-emergence in Huang-Huai River of central China. *Malaria Journal*, **9**, 337, doi: 10.1186/1475-2875-9-337.

Zhou, X., G. Yang, K. Yang, X. Wang, Q. Hong, L. Sun, J.B. Malone, T.K. Kristensen, N.R. Bergquist, and J. Utzinger, 2008: Potential impact of climate change on schistosomiasis transmission in China. *American Journal of Tropical Medicine and Hygiene*, **78(2)**, 188-194.

Zhu, B.P., 2005: Effect of interpregnancy interval on birth outcomes: findings from three recent US studies. *International Journal of Gynecology & Obstetrics*, **89(Suppl. 1)**, S25-S33.

12 Human Security

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This chapter should be cited as:
Adger, W.N., J.M. Pulhin, J. Barnett, G.D. Dabelko, G.K. Hovelsrud, M. Levy, Ú. Oswald Spring, and C.H. Vogel, 2014: Human security. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 755-791.

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Executive Summary

Human security will be progressively threatened as the climate changes (*robust evidence*, *high agreement*). Human insecurity almost never has single causes, but instead emerges from the interaction of multiple factors. {12.1.2, 12.2} Climate change is an important factor threatening human security through (1) undermining livelihoods {12.2}; (2) compromising culture and identity {12.3}; (3) increasing migration that people would rather have avoided {12.4}; and (4) challenging the ability of states to provide the conditions necessary for human security. {12.6}

Climate change will compromise the cultural values that are important for community and individual well-being (*medium evidence*, *high agreement*). The effect of climate change on culture will vary across societies and over time, depending on cultural resilience and the mechanisms for maintaining and transferring knowledge. Changing weather and climatic conditions threaten cultural practices embedded in livelihoods and expressed in narratives, world views, identity, community cohesion, and sense of place. Loss of land and displacement, for example on small islands and coastal communities, has well documented negative cultural and well-being impacts. {12.3.1, 12.3.3, 12.4.2}

Indigenous, local, and traditional forms of knowledge are a major resource for adapting to climate change (*robust evidence*, *high agreement*). Natural resource dependent communities, including indigenous peoples, have a long history of adapting to highly variable and changing social and ecological conditions. But the salience of indigenous, local, and traditional knowledge will be challenged by climate change impacts. Such forms of knowledge are often neglected in policy and research, and their mutual recognition and integration with scientific knowledge will increase the effectiveness of adaptation. {12.3.3-4}

Climate change will have significant impacts on forms of migration that compromise human security (*medium evidence*, *high agreement*). Some migration flows are sensitive to changes in resource availability and ecosystem services. Major extreme weather events have in the past led to significant population displacement, and changes in the incidence of extreme events will amplify the challenges and risks of such displacement. Many vulnerable groups do not have the resources to be able to migrate to avoid the impacts of floods, storms, and droughts. Models, scenarios, and observations suggest that coastal inundation and loss of permafrost can lead to migration and resettlement. {12.4.2} Migrants themselves may be vulnerable to climate change impacts in destination areas, particularly in urban centers in developing countries. {12.4.1.2}

Mobility is a widely used strategy to maintain livelihoods in response to social and environmental changes (*medium evidence*, *high agreement*). Migration and mobility are adaptation strategies in all regions of the world that experience climate variability. Specific populations that lack the ability to move also face higher exposure to weather-related extremes, particularly in rural and urban areas in low- and middle-income countries. Expanding opportunities for mobility can reduce vulnerability to climate change and enhance human security. {12.4.1-2} There is insufficient evidence to judge the effectiveness of resettlement as an adaptation to climate change.

Some of the factors that increase the risk of violent conflict within states are sensitive to climate change (*medium evidence*, *medium agreement*). The evidence on the effect of climate change and variability on violence is contested. {12.5.1} Although there is little agreement about direct causality, low per capita incomes, economic contraction, and inconsistent state institutions are associated with the incidence of violence. {12.5.1} These factors can be sensitive to climate change and variability. Poorly designed adaptation and mitigation strategies can increase the risk of violent conflict. {12.5.2}

People living in places affected by violent conflict are particularly vulnerable to climate change (*medium evidence*, *high agreement*). Evidence shows that large-scale violent conflict harms infrastructure, institutions, natural capital, social capital, and livelihood opportunities. Since these assets facilitate adaptation to climate change, there are grounds to infer that conflict strongly influences vulnerability to climate change impacts. {12.5.3}

Climate change will lead to new challenges to states and will increasingly shape both conditions of security and national security policies (*medium evidence*, *medium agreement*). Physical aspects of climate change, such as sea level rise, extreme events, and hydrologic disruptions, pose major challenges to vital transport, water, and energy infrastructure. {12.6} Some states are experiencing major challenges to their territorial integrity, including small island states and other states highly vulnerable to sea level rise. {12.6.2} Some transboundary impacts of climate change, such as changes in sea ice, shared water resources, and the migration of fish stocks, have the potential to increase rivalry among states. The presence of robust institutions can manage many of these rivalries such that human security is not severely eroded. {12.5.1, 12.6.2}

12.1. Definition and Scope of Human Security

There are many definitions of human security, which vary according to discipline. This chapter defines human security, in the context of climate change, as a condition that exists when the vital core of human lives is protected, and when people have the freedom and capacity to live with dignity. In this assessment, the vital core of human lives includes the universal and culturally specific, material and non-material elements necessary for people to act on behalf of their interests. Many phenomena influence human security, notably the operation of markets, the state, and civil society. Poverty, discrimination of many kinds, and extreme natural and technological disasters undermine human security.

The concept of human security has been informed and debated by many disciplines and multiple lines of evidence, by studies that use diverse methods (Paris, 2001; Alkire, 2003; Owen, 2004; Gasper, 2005; Hoogensen and Stuvøy, 2006; Mahoney and Pinedo, 2007; Brauch et al., 2009; Inglehart and Norris, 2012). The concept was developed in parallel by UN institutions, and by scholars and advocates in every region of the world (UNDP, 1994; Commission on Human Security, 2003; Najam, 2003; Kaldor, 2007; Black and Swatuk, 2009; Chourou, 2009; Othman, 2009; Poku and Sandkjaer, 2009; Rojas, 2009; Sabur, 2009; Wun Gaeo, 2009).

This chapter assesses the risks climate change poses to individuals and communities, including threats to livelihoods, culture, and political stability. Chapters in Working Group II (WGII) in the Fourth Assessment Report (AR4) identified the risk climate change poses to livelihoods, cultures, and indigenous peoples globally (Chapters 5, 7, 9 10, 16, and 17) and that migration and violent conflicts increase vulnerability to climate change (Chapter 19), as well as highlighting that migration plays a role in adaptation. But this chapter is the first systematic assessment across the dimensions of human security.

Research since publication of the AR4 has addressed the linkages between climate change and human security through concerted international research programs and initiatives (Afifi and Jäger, 2010; Matthew et al., 2010; O'Brien et al., 2010; Gleditsch, 2012; Oswald Spring, 2012; Scheffran et al., 2012a; Sygna et al., 2013). Specific dimensions of human security, such as food security, public health and well-being, livelihoods, and regional perspectives, are examined systematically in Chapters 11, 13, and 19, and in Chapters 22 to 29 of this report, and this chapter cross-refers to those assessments.

The assessment in this chapter is based on structured reviews of scientific literature. These were carried out first using searches of scientific databases of relevant studies published from 2000 until 2013, with searches targeted at the core dimensions of culture, indigenous peoples, traditional knowledge, migration, conflict, and transboundary resources. These searches were supplemented by open searches to capture book and other non-journal literature. The comprehensive review in this chapter reflects the dominant findings from the scientific literature that the impacts of climate change on livelihoods, cultures, migration, and conflict are negative, but that some dimensions of human security are less sensitive to climate change and driven by economic and social forces.

This chapter assesses research on how climate change may exacerbate specific threats to human security, and how factors such as lack of mobility or the presence of conflict restrict the ability to adapt to climate change. Research on the specific interaction of human security and climate change focuses on how cultural, demographic, economic, and political forces interact with direct and indirect climate change impacts, affecting individuals and communities (Krause and Jütersonke, 2005; Hoogensen and Stuvøy, 2006; O'Brien, 2006; Betancourt et al., 2010; Sygna et al., 2013). The analysis concerns drivers of vulnerability across multiple scales and sectors, including gender relations, culture, political institutions, and markets. Each of these areas has its distinct disciplinary focus, methods, and levels of evidence as discussed in Box 12-2.

Human security and insecurity are universal issues. In every country there are individuals and groups who are insecure (Mahoney and Pinedo, 2007; Pietsch and McAllister, 2010). Much research suggests that while the impacts of climate change on human security will be experienced

Box 12-1 | Relationship between Human Rights and Human Security in the Context of Climate Change

This chapter focuses on human security, but does not explicitly frame the issue as one of rights. The argument is made in political and legal scholarship that human rights to life, health, shelter, and food are fundamentally breached by the impacts of climate change. Climate change puts both human security and human rights at risk (Slade, 2007; Caney, 2010; Humphreys, 2010). But framing the issue of rights specifies minimum standards that apply universally, and such rights are often not realized in national and international law and practice or neglect the harm or rights of nonhuman species (Humphreys, 2010; Bell, 2013). Human security by contrast is inclusive of political, sociocultural, and economic rights, rather than legal rights (CHS, 2003), which are instrumental to its achievement (Bell, 2013).

Research on climate change risks to human rights examines legal issues in policy, litigation, and compensation (Posner, 2007). Many legal commentators argue that claims to human rights may ultimately not offer greater explanation of the harm to individuals or realize political traction in climate policy (Carlane and Depledge, 2007; Adelman, 2010; Bodansky, 2010). Several cases have tested these rights, especially of women, children, indigenous peoples, and other minorities (Oswald Spring, 2008; Knox, 2009; Bodansky, 2010).

Box 12-2 | The Nature of Evidence about Climate Change and Human Security

Understanding the effects of climate change on human security requires evidence about social and environmental processes across multiple scales and sectors. This process-based analysis is informed by a wide array of theories, methods, and evidence used in different academic disciplines, and so is not contiguous. For example, this chapter assesses anthropological research where culture influences responses to climate change or may be shaped by climate change; alongside political and economic studies which use data sets to test for correlations between climatic factors and violent conflicts; and historical observations using documentary and archaeological methods. These diverse sources strengthen the robustness of the conclusions for this assessment when they converge on similar findings (Van de Noort, 2011; Nielsen and Reenberg, 2012).

This chapter reviews empirical studies from the social and physical sciences using both quantitative and qualitative data. Some studies examine the interactions between environmental changes and social outcomes. Few explicitly address climate change and human security links, but provide evidence of climate change impacts on human security (Ford et al., 2010). Individual case studies often make causal claims in given contexts, but their results may not be generalized. Where results from multiple comparative case studies agree, generalization is sometimes possible. This chapter also assesses quantitative studies about large social units with correlations among different factors. Correlations alone do not explain causality, although they are important in testing theories.

Given the many and complex links between climate change and human security, uncertainties in the research on the biophysical dimensions of climate change, and the nature of the social science, highly confident statements about the influence of climate change on human security are not possible (Scheffran et al., 2012a). Yet there is good evidence about many of the discrete links in the chains of causality between climate change and human insecurity. In this chapter the standardized IPCC language of uncertainty is applied to those linkages where appropriate.

Many climate change risks to human security warrant further investigation. There is a need for more comprehensive evidence, collected across multiple locations, and over long durations, to build and test theories about relationships between climate change and livelihoods, culture, migration, and conflict. Meeting this need requires analysis of the sensitivity of diverse livelihood systems to climate change; and the effects of cultural, economic, and political changes on the vulnerability and adaptability of livelihoods. Questions surrounding the cultural dimensions of climate require much more research using multiple methods to enable more general conclusions to be drawn, in particular about the effects of culture on climate change mitigation and adaptation. The sensitivity of human mobility to climate also requires new investigation, including, importantly, systematic long-term monitoring of population changes. The effects of migration on the vulnerability and adaptation of migrants, migrant sending areas, and destination communities also warrants more research, to permit scope for targeted policy interventions to reduce vulnerability. Finally, with respect to advancing knowledge of climate change and violence, extensive as well as case-based research is necessary to build theories of causality, including examination of cases where climate changes and variability were managed peacefully, in addition to cases where conflict emerged. Explanations of processes that reduce violence despite climate variability and change are necessary for responses that help sustain and improve peace in a future where the climate is changing.

most in developing countries, human security is at risk for vulnerable populations everywhere (Naess et al., 2006; Leichenko and O'Brien, 2008; Berrang-Ford et al., 2011).

The chapter also evaluates research on the interaction between the state and human security, suggesting that increased human insecurity may coincide with a decline in the capacity of states to conduct effective adaptation efforts, thus creating circumstances in which there is greater potential for violent conflict, especially in the absence of means to resolve conflicts effectively. The analysis extends to assess how states protect the human security of their citizens. In other words, this chapter examines the security of the state because it directly impinges on human security by affecting the ability of states to protect their citizens.

The framing of climate change as a security issue has been controversial. Some authors suggest that discourses on climate change and national security tend to downplay human security dimensions and skew mitigation and adaptation responses toward state interests rather than those of

the most vulnerable human populations (Barnett 2007, 2009; Floyd, 2008; Brauch, 2009; Dalby, 2009; Verhoeven, 2009; Trombetta, 2012; Oels, 2013). Nevertheless, some countries associate climate change risks with conventional security risks and many countries are concerned about the risks climate change poses to relations between states (see Sections 12.5 and 12.6). This chapter therefore adopts a comprehensive approach to human security, which is widely supported in the literature (Barnett, 2001; Brauch et al., 2008, 2009, 2011; Matthew et al., 2010; O'Brien et al., 2010; Oswald Spring, 2012).

12.2. Economic and Livelihood Dimensions of Human Security at Risk from Climate Change

12.2.1. Climate Change Impacts on Material Aspects of Livelihood Security

The direct and material aspects of livelihood security include access to food, housing, clean water, employment, and the avoidance of direct risks to health. Chapters 7, 11, and 13 assess the evidence of the mechanisms that link climate change with these phenomena. They find that climate change poses significant risks in all these areas and all conclude that material aspects of life and livelihood such as food, water, and shelter are closely coupled to weather and climate but also to multiple factors in the economy and society (Battisti and Naylor, 2009; Bohle, 2009; Hertel et al., 2010; Schlenker and Lobell, 2010; Deligiannis, 2012; see also Section 13.1.4). Hence, although attributing changes in climate directly to human security is difficult, some major risks are well documented. This chapter builds on that knowledge base to assess the interaction of those risks with cultural dimensions of change, and the risks of migration and conflict. It is well established that direct risks of climate change to life and livelihoods are highly differentiated by socio-demographic factors, such as by age, wealth, and gender. Box CC-GC, for example, highlights how specific populations of men and women are vulnerable to weather extremes.

Table 12-1 summarizes studies that exemplify how climate variability and change affect the material aspect of human security through deprivation of immediate basic needs and erosion of livelihood assets

Table 12-1 | Illustrative examples of impacts of climate variability and change on immediate basic needs and longer term capabilities and assets from observational studies and from projections.

Dimensions of impact		Illustrative examples of observed impacts due to aggravating climate stresses	Illustrative examples of potential changes in livelihoods and capabilities as a consequence of climate variability and climate change
Deprivation of basic needs	Livelihood assets	Household assets such as livestock sold or lost during drought: documented examples are the 1999–2000 drought, Ethiopia, and 1999–2004 drought, Afghanistan (Carter et al., 2007; de Weijer 2007). Riverbank erosion, floods, and groundwater depletion and salinization are associated with changed hydrological regimes and cause loss of agricultural land (Paul and Routray, 2010; Taylor et al., 2013).	Simulated future climate volatility leads to reduced future production of staple grains and increases in poverty (Ahmed et al., 2009). Changes in the viability of livestock feed crops have an impact on smallholder farmers: maize yields are projected to decline in many regions (Jones and Thornton, 2003; Section 7.4). Projections of land loss, riverbank erosion, and groundwater depletion, in combination with environmental change and human interventions, suggest future stress on livelihood assets (Le et al., 2007; Taylor et al., 2013).
	Water stress and scarcity	Glacier retreat leads to lower river flows and hence affects water stress and livelihoods, representing a cultural loss (Orlove et al., 2008). For example, glacier recession in the Cordillera Blanca in Peru has altered the hydrological regime with implications for local livelihoods and water availability downstream (Mark et al., 2010).	Projected stresses to water availability show increased populations without sustainable access to safe drinking water (Hadipuro, 2007). Projected reduction in glacier extent and the associated loss of a hydrological buffer is expected to increase (Vuille, 2008; Section 3.4.4).
	Loss of property and residence	Floods destroy shelter and properties and curtail ability to meet basic needs. For example, the Fiji flood in 2009 resulted in economic losses of F$24 million affecting at least 15% of farm households (Lal, 2010). Sea level rise and increased frequency of extreme events increases the risk of loss of lives, homes, and properties and damages infrastructure and transport systems (Adrianto and Matsuda, 2002; Suarez et al., 2005; Philips and Jones, 2006; Ashton et al., 2008; Von Storch et al., 2008).	Changes in flood risk may increase and cause economic damages: in the Netherlands, the total amount of urban area that can potentially be flooded has increased sixfold during the 20th century and may double again during the 21st century (de Moel et al., 2011). In England and Wales, projected changes in flood risk mean economic damages may increase up to 20 times by the 2080s (Hall et al., 2003).
Erosion of livelihood and human capabilities	Agriculture and food security	Interaction of climate change with poverty and other political, social, institutional, and environmental factors may adversely affect agriculture production and exacerbate the problem of food insecurity (Downing, 2002; Saldana-Zorrilla, 2008; Trotman et al., 2009). Examples include in Kenya (Oluoko-Odingo, 2011); in Southern Africa (Drimie and Gillespie, 2010); in Zimbabwe and Zambia (Mubaya et al., 2012).	Studies of African agriculture using diverse climate scenarios indicate increasing temperature and rainfall variation have negative impacts on crops and livestock production and lead to increased poverty, vulnerability, and loss of livelihoods. Examples include Ethiopia (Deressa and Hassan, 2009); Kenya (Kabubo-Mariara, 2009); Burkina Faso, Egypt, Kenya, and South Africa (Molua et al., 2010); and sub-Saharan Africa (Jones and Thornton, 2009). Potential livelihood insecurity among small-scale rain-fed maize farmers in Mexico is projected owing to potential loss of traditional seed sources in periods of climate stress (Bellona et al., 2011).
	Human capital (health, education, loss of lives)	Food shortage, absence of safe and reliable access to clean water and good sanitary conditions, and destruction of shelters and displacements all have a negative bearing on human health (Costello et al., 2009; Sections 11.4 and 11.8). Droughts and floods can intensify the pressure to transfer children to the labor market (Ethiopia and Malawi; UNDP, 2007). Indian women born during a drought or flood in the 1970s were 19% less likely to ever attend primary school, when compared with women of the same age who were not affected by natural disasters (UNDP, 2007).	Analysis of the economic and climatic impacts of three emission scenarios and three tax scenarios estimates the impacts on food productivity and malaria infection to be very severe in some Asian countries (Kainuma et al., 2004). Studies of the impacts of future floods using a combination of socioeconomic and climate change scenarios for developed countries show an increase in mortality. For example, in the Netherlands, sea level rise, combined with other factors, potentially increases the number of fatalities four times by 2040 (Maaskant et al., 2009).

Frequently Asked Questions

FAQ 12.1 | What are the principal threats to human security from climate change?

Climate change threatens human security because it undermines livelihoods, compromises culture and individual identity, increases migration that people would rather have avoided, and because it can undermine the ability of states to provide the conditions necessary for human security. Changes in climate may influence some or all of the factors at the same time. Situations of acute insecurity, such as famine, conflict, and sociopolitical instability, almost always emerge from the interaction of multiple factors. For many populations that are already socially marginalized, resource dependent, and have limited capital assets, human security will be progressively undermined as the climate changes.

and human capabilities. There are well-established links from climate variability and change to the stability of agriculture and food security, water stress and scarcity, as well as destruction of property (Carter et al., 2007; Leary et al., 2008; Paavola, 2008; Peras et al., 2008; Tang et al., 2009). Projections using various socioeconomic and climate change scenarios indicate an increase in economic and health risks, including loss of lives in all regions (Hall et al., 2003; Kainuma et al., 2004; Tang et al., 2009) as well as a range of psychological stresses accompanying extreme climate events and decreased access to ecosystem resources (e.g., Doherty and Clayton, 2011). The cross chapter box on Heat Stress (Box CC-HS), for example, documents the evidence on the impacts of heat stress on both labor productivity and on health outcomes.

Modeled and observational analysis of human exposure to climate-related natural disasters finds significant risk of large human losses, particularly in countries with significant populations in poverty (Peduzzi et al., 2009; Busby et al., 2013). Table 12-1, and the analysis in cognate chapters (Sections 7.3, 11.3, 13.2.2), shows that risks are significant and well understood though there is uncertainty about how dimensions of basic needs, livelihoods, and the integrity of place and economic assets will unfold under scenarios of climate change. Those cognate chapters confirm that elements of nutrition, economic stability, and threats to shelter and human health interact with each other and all represent significant challenges for adaptation. Following from this body of evidence, a number of studies conclude that adverse impacts of climate change on health and on human capital will lead to the erosion of human capability (UNDP, 2007; Costello et al., 2009).

12.2.2. Adaptation Actions and Livelihood Dimensions of Human Security

Adaptation strategies seek to reduce vulnerability and thereby advance human security. But they also run the risk of exacerbating elements of insecurity (e.g., Deligiannis, 2012; see also Section 12.2.2). Evaluations of development interventions, for example, provide robust evidence on how livelihoods can be secured and enhanced through adaptation in the context of external shocks and shorter-term climate stresses (e.g., Ellis, 2000; Dercon, 2004). But an emerging literature documents how some adaptation interventions can create new risks, are inefficient, or fail to recognize wider goals of system resilience (e.g., Eriksen et al., 2011; Adger et al., 2011b; see also Sections 13.3.2 and 20.3.2).

Adaptation interventions and strategies have been documented that reduce risks to human security, but vary in effectiveness. Strategies that have been documented as promoting well-being include (1) diversification of income-generating activities in agricultural and fishing systems (Coulthard, 2008; Paavola, 2008; Tolossa, 2008; Galvin, 2009; Badjeck et al., 2010; West and Hovelsrud, 2010); (2) migration as a risk management strategy, for example, among pastoralists and farmers in rainfed areas (Galvin, 2009) and among fishing communities (Perry and Sumaila, 2007; Badjeck et al., 2009); (3) the development of insurance systems, particularly among vulnerable groups (Linneroth-Bayer and Vari, 2008; Badjeck et al., 2010); and (4) the education of women (Boyle et al., 2006; Rammohan and Johar, 2009). Some adaptation strategies may, however, undermine human security, particularly where strategies are implemented without taking cognizance of complex livelihood arrangements. In some cases, adaptations may entrench vulnerabilities and also have the potential to enforce inequalities (Barnett and O'Neill, 2010). For example, in parts of the Middle East and North Africa, the Andes, and the Caribbean, among other areas, skewed water policy allocation in some cases that favor the affluent may heighten overall livelihood vulnerabilities to climate stress (Section 13.2.1.1).

12.3. Cultural Dimensions of Human Security

12.3.1. How Culture Interacts with Climate Impacts and Adaptation

Culture is a contested and highly fluid term that is defined in this chapter as material and non-material symbols that express collective meaning. In all societies culture is expressed in knowledge, worldviews, beliefs, norms, values, and social relationships (Crate, 2008, 2011; Heyd, 2008; Roncoli et al., 2009; Strauss, 2009; O'Brien and Wolf, 2010; Tingley et al., 2010; Rudiak-Gould, 2012; Sudmeier-Rieux et al., 2012). In this definition culture shapes the relationship of society to environments and is a significant determinant of responses to environmental and other risks and challenges (Siurua and Swift, 2002; Pearce et al., 2009; Buikstra et al., 2010; Nielsen and Reenberg, 2010; Petheram et al., 2010; Paul and Routray, 2011).

There has been significant new research from psychology, anthropology, sociology, and human geography in the period since AR4 on the lived experience of weather extremes and observed climate change, driven

Box 12-3 | Food Prices, Food Insecurity, and Links to Climate

Food prices and food-price shocks have significant impacts on human security. They do so through reduced access to, and production of, food that affects both consumers and food producers (e.g., Sections 7.4.3, 13.2.1-2; Barrett, 2010). It is well established that food security is determined by a range of interacting factors including poverty, water availability, food policy agreements and regulations, and the demand for productive land for alternative uses (Barrett, 2010, 2013). It is also established that many of these factors are themselves sensitive to climate variability and climate change. Specific observed food prices have, however, multiple causes and complex dynamics between markets, non-food demand for agricultural land, and the impact of adverse weather and droughts on the major agricultural producing regions (Piesse and Thirtle, 2009).

Spikes in food prices have particularly acute impacts on food insecurity at the domestic level, even in the absence of climate stresses. There was, for example, high regional variation in self-reported food insecurity following the global 2008 price spike: the reported food insecurity was especially serious across Africa and Latin American countries (Headey, 2013). The 2010–2011 food price spike has been estimated to have pushed 44 million people below the basic needs poverty line across 28 countries (Ivanic et al., 2012). Food availability can also be affected by domestic production of food, particularly for those countries where there are restrictions on food imports (Barrett, 2013; Berazneva and Lee, 2013). There are, therefore, multiple pathways by which consumers including agricultural wage laborers in low-income countries are affected (Mendelsohn et al., 2007; Ahmed et al., 2009; Cohen and Garrett, 2010; Hertel and Rosch, 2010; Ruel at al., 2010). Declines in agricultural productivity linked to climate variability and losses in maize production, for example, have been shown in Zambia to reduce real urban incomes and to influence urban poverty for a portion of the population (Thurlow et al., 2012).

Food prices and food availability also affect socio-political stability and in the case of the 2008–2009 and 2010–2011 food price spikes have been associated with food riots (Johnstone and Mazo, 2011; Barrett, 2013; Berazneva and Lee, 2013). High food prices affect food access and food availability, but such insecurity is highly conditional on the responses of markets and governments and hence is variable. Berazneva and Lee (2013) show that 14 countries in Africa experienced food riots in 2008 and that they are characterized by higher levels of poverty, restricted food access and availability, are more urbanized, and have more oppressive regimes and stronger civil societies than those countries that did not experience riots. The linkages between food riots and climate change are therefore dependent on responses of multiple private and state actors and it is generally concluded that it is difficult to attribute causality (Barrett, 2013).

Food prices, food access, and food availability are critical elements of human security. There is robust evidence that food security affects basic-needs elements of human security and, in some circumstances, is associated with political stability and climate stresses. But there are complex pathways between climate, food production, and human security and hence this area requires further concentrated research as an area of concern.

in part by observed warming trends in regions. This body of knowledge from across social science disciplines argues that climate change is embedded in and acts on culture in myriad ways. For example, all consumption patterns are culturally embedded and therefore culture influences greenhouse gas emissions. The phenomenon of climate change itself is perceived differently depending on the culture in which it is viewed, with scientific expression representing only one possibility (Norgaard, 2011). Similarly, there are widely different cultural expressions of weather, risk, and the need for adaptation to such hazards (Hulme, 2008; Adger et al., 2013). Therefore, since climate change has consequences for people this emerging body of knowledge shows with *high confidence* that climate change has significant cultural implications (Crate, 2011; Strauss, 2012).

Anthropological analysis of culture focuses on identity, community, and economic activities. There is a growing body of research on how climate and other environmental change affects livelihood activities such as pastoralism, herding, farming, fishing and hunting, and gathering in places where there is significant observed change. Research has documented how rural livelihoods and, therefore, cultural practices have been affected by changes in climate and associated impacts on natural capital. Many anthropological studies suggest that further significant changes in the

natural resource base on which many cultures depend would directly affect the cultural core, worldviews, cosmologies, and mythological symbols of indigenous cultures (Crate, 2008; Gregory and Trousdale, 2009; Jacka, 2009). While changing socioeconomic and environmental conditions may constrain existing community coping mechanisms (Rattenbury et al., 2009; West and Hovelsrud, 2010; Quinn et al., 2011), other studies focus on how cultures adapt to significant societal and environmental changes. Many successful examples of the persistence of cultures despite significant upheaval exist throughout history (Nuttall, 2009; Cameron, 2012; Strauss, 2012).

Culture also interacts with adaptation through the way that cultural, local, and individual perceptions affect narratives of risk, resilience, and adaptive capacity. A body of research across disciplines argues that incorporation of cultural understanding of environment, risk, and social practices increases the explanatory power of models of risk (Ifejika Speranza et al., 2008; Jacka, 2009; Adger et al., 2011a). The way in which resource-dependent communities articulate and perceive climate change is often based on how English language terms are translated and understood in the local language (Rudiak-Gould, 2012). Furthermore, information is interpreted through personal life stories and culture (Kuruppu and Liverman, 2011). Local perceptions of what kind of knowledge is trustworthy may in fact lead to questioning of scientific findings (Ingram et al., 2002; Burns et al., 2010; Roncoli et al., 2011). Table 12-2 illustrates different dimensions in which climate change is interpreted and through which human security is affected.

Culturally embedded perceptions of climate change may either facilitate or hinder adaptation with implications for human security (Zamani et al., 2006; Burningham et al., 2008; West and Hovelsrud, 2010; Gómez-Baggethun et al., 2012; Nursey-Bray et al., 2012; Rudiak-Gould, 2012). Scientific information on weather variability and change is framed through cultural practices that can both enable (Dannevig et al., 2012) and constrain (Roncoli, 2006) adaptation. There are a number of anthropological studies that document how some cognitive frames do not perceive a changing climate and hence the concept of climate change itself does not have cultural resonance, whether or not the parameters of climate have been observed (Kuruppu and Liverman, 2011; Lipset, 2011; Sánchez-Cortés and Chavero, 2011; Rudiak-Gould, 2012). Most of these studies conclude that climate policies do not have legitimacy and salience when they do not consider how individual behavior and collective norms are embedded in culture (Stadel, 2008; Jacka, 2009).

There is a significant body of research that analyzes community and collective action for adaptation and generally finds positive outcomes. Many studies conclude that community-led action is effective for reducing risks and building capacity for adaptation (Davidson et al.,

Table 12-2 | Cultural dimensions of climate science, policy, impacts, and extreme events in the context of climate change.

Core climate change dimensions	Cultural dimensions	Role in human security	Sources
Climate science and policy	Framing of climate change in a dominant language Global climate change policy implemented at international scales	How concepts and uncertainties are translated, imported, and incorporated can facilitate or hinder adaptation: *Facilitate adaptation*: available explanatory tools; successful translation of climate change impacts; awareness of culture *Hinder adaptation*: lack of trust in science and in policy; policy not recognizing the connection between nature and culture Policy and decision making that is inclusive of cultural perspectives *increases security*.	Ifejika Speranza et al. (2008); Stadel (2008); Jacka (2009); Green et al. (2010); Osbahr et al. (2010); Schroeder (2010); Gero et al. (2011); Kuruppu and Liverman (2011); Roncoli et al. (2011); Sánchez-Cortés and Chavero (2011); McNeely (2012); Rudiak-Gould (2012)
Impacts of environmental conditions, extreme events, and changing natural resource base	Elements of collective understanding such as: • Worldviews • Coupling of nature–culture • Power relations • Heterogeneity within groups and communities	*Facilitate adaptation*: New technologies; livelihood diversification and flexibility; perceptions of resilience; narratives and history about past changes and current conditions; co-management of resources increases adaptive capacity. *Hinder adaptation*: limitations of local knowledge; lack of awareness and understanding of culture constrains action; knowledge and cultural repertoire limited for responding to new challenges; perceptions of resilience Erosion of cultural core potentially *decreases human security*. Institutional responses and resource management will impact human security either negatively or positively.	Nunn (2000); Davidson et al. (2003); Desta and Coppock (2004); Ford et al. (2006, 2008); Furgal and Seguin (2006); Kesavan and Swaminathan (2006); Zamani et al. (2006); Nyong et al. (2007); Tyler et al. (2007); Angassa and Oba (2008); Burningham et al. (2008); Crate (2008); de Sherbinin et al. (2008); King (2008); Gregory and Trousdale (2009); Jacka (2009); Pearce et al. (2009); Berkes and Armitage (2010); Dumaru (2010); Fazey et al. (2010); Hovelsrud and Smit (2010); Hovelsrud et al. (2010a,b); Kalikoski et al. (2010); Kuhlicke (2010); Lefale (2010); Nielsen and Reenberg (2010); Osbahr et al. (2010); Rybråten and Hovelsrud (2010); Valdivia et al. (2010); West and Hovelsrud (2010); Armitage et al. (2011); Gero et al. (2011); Harries and Penning-Rowsell (2011); Kuruppu and Liverman (2011); Marshall (2011); Onta and Resurrection (2011); Roncoli et al. (2011); Adler et al. (2012); Anik and Khan (2012); Eakin et al. (2012); Ford and Goldhar (2012); Gómez-Baggethun et al. (2012); McNeeley (2012); Nursey-Bray et al. (2012); Rudiak-Gould (2012); Sudmeier-Riuex et al. (2012)
Scientific observations, monitoring, models, projections, scenarios	Local, traditional, and indigenous knowledge through observations and experience	*Facilitate adaptation*: mutual integration of traditional, local, and scientific knowledge; climate projections with local relevance; intergenerational knowledge transfers Local knowledge included in climate policy and decision making *increases human security*. Knowledge not included in adaptation planning *decreases human security*.	Orlove et al. (2000, 2010); Ingram et al. (2002); Tàbara et al. (2003); Alcántara-Ayala et al. (2004); Roncoli (2006); Anderson et al. (2007); Forbes (2007); Nyong et al. (2007); Tyler et al. (2007); Vogel et al. (2007); Catto and Parewick (2008); Marfai et al. (2008); Mercer et al. (2009); Pearce et al. (2009); Burns et al. (2010); Frazier et al. (2010); Gearheard et al. (2010); Hovelsrud and Smit (2010); Marin (2010); Mark et al. (2010); Smit et al. (2010); Flint et al. (2011); Huntington (2011); Kalanda-Joshua et al. (2011); Ravera et al. (2011); Sánchez-Cortés and Chavero (2011); Dannevig et al. (2012); Eira et al. (2013)

2003; Furgal and Seguin, 2006; Catto and Parewick, 2008; Fazey et al., 2010; Gero et al., 2011; Harries and Penning-Rowsell, 2011; Anik and Khan, 2012; Sudmeier-Riuex et al., 2012; Adler, et al., 2013). Specifically, this literature finds that community participation in risk and vulnerability assessments produces more sustainable solutions (Ardalan et al., 2010; Gero et al., 2011) and that co-management of resources and learning increase adaptive capacity (Ford et al., 2007; Dumaru, 2010; Fazey et al., 2010; Armitage et al., 2011). Much of this literature recognizes, however, the structural barriers to community-led action and limited participation that can hinder effective community adaptation to climate change (Singleton, 2000; Davidson et al., 2003; King, 2008; Ensor and Berger, 2009; Nielsen and Reenberg, 2010; Onta and Resurrection, 2011). Further studies highlight barriers to widespread community responses that result from colonial history (Marino, 2012) and from political and economic globalization (O'Brien et al., 2004; Keskitalo, 2009).

12.3.2. Indigenous Peoples

There are around 400 million indigenous people worldwide (see Glossary for an inclusive definition), living under a wide range of social, economic, and political conditions and locations (Nakashima et al., 2012). Indigenous peoples represent the world's largest reserve of cultural diversity and the majority of languages (Sutherland, 2003). Climate change poses challenges for many indigenous peoples, including challenges to post-colonial power relations, cultural practices, their knowledge systems, and adaptive strategies. For example, the extensive literature on the Arctic shows that changing ice conditions pose risks in terms of access to food and increasingly dangerous travel conditions (Ford et al., 2008, 2009; Hovelsrud et al., 2011; see also Section 28.4.1). Accordingly, there is a strong research tradition on the impacts of climate change in regions with substantial indigenous populations that focuses on indigenous peoples and their attachment to place. Most studies focus on local, traditional, and rural settings (Cameron, 2012) and hence have been argued to create a knowledge gap regarding new urban indigenous populations. Indigenous peoples are often portrayed in the literature as victims of climate change (Salick and Ross, 2009) and as vulnerable to its consequences (ACIA, 2005). However, traditional knowledge is increasingly being combined with scientific understanding to facilitate a better understanding of the dynamic conditions of indigenous peoples (Huntington, 2011; see also Section 12.3.4).

There is *high agreement* that, historically, indigenous peoples have had a high capacity to adapt to variable environmental conditions. This literature also suggests indigenous peoples also have less capacity to cope with rapidly changing socioeconomic conditions and globalization (Tyler et al., 2007; Crate and Nuttall, 2009). Documented challenges for indigenous cultures to adapt to colonization and globalization may reflect resilience and the determination of indigenous peoples to maintain cultures and identities. Furthermore, historical legacies affect the way that indigenous populations adapt to modern challenges: anthropological research has documented clear linkages between historical colonization and the way the way indigenous peoples respond to current climatic changes (Salick and Ross, 2009; Cameron, 2012; Howitt et al., 2012; Marino, 2012).

Most of the literature in this area emphasizes the significant challenge of maintaining cultures, livelihoods, and traditional food sources under the impacts of climate change (Crate and Nuttall, 2009; Rybråten and Hovelsrud, 2010; Lynn et al., 2013). Examples from the literature show that traditional practices are already under pressure from multiple sources, reducing the ability of such practices to enable effective responses to climate variability (Green et al., 2010). Empirical evidence suggests that the efficacy of traditional practices can be eroded when governments relocate communities (Hitchcock, 2009; McNeeley, 2012; Maldonado et al., 2013); if policy and disaster relief creates dependencies (Wenzel, 2009; Fernández-Giménez et al., 2012); in circumstances of inadequate entitlements, rights, and inequality (Shah and Sajitha, 2009; Green et al., 2010; Lynn et al., 2013); and when there are constraints to the transmission of language and knowledge between generations (Forbes, 2007). Some studies show that current indigenous adaptation strategies may not be sufficient to manage the projected climate changes (Wittrock et al., 2011).

Assessments of the cultural implications of climate change for human security illustrate similarities across indigenous peoples. Indigenous peoples have a right to maintain their livelihoods and their connections to homeland and place (Howitt et al., 2012) and it is suggested that the consequences of climate change are challenging this right (Box 12-1; Crate and Nuttall, 2009). Some raise the question whether the Western judicial system can uphold indigenous rights in the face of climate change (Williams, 2012) and that there is a need for justice that facilitates adaptation (Whyte, 2013). In addition, there are uneven societal consequences related to climate change impacts (e.g., use of sea ice: Ford et al., 2008), which add complexity to adaptation in indigenous societies. Heterogeneity within indigenous groups and differentiated exposure to risk has been found in other contexts, for example, in pastoralist groups of the Sahel (Barrett et al., 2001).

Much research on indigenous peoples concludes that lack of involvement in formal, government decision making over resources decreases resilience: the literature recommends further focus on indigenous perceptions of risk and traditional knowledge of change, hazards, and coping strategies and collective responses (Ellemor, 2005; Brown, 2009; Finucane, 2009; Turner and Clifton 2009; Sánchez-Cortés and Chavero, 2011; Maldonado et al., 2013). Though providing economic opportunities, tourism development and industrial activities are particular areas of risk for indigenous peoples when affected populations are not involved in decision making (Petheram et al., 2010). Lack of formal participation in international negotiations may pose risks for indigenous peoples because their perspectives are not heard (Schroeder, 2010). However, there are examples of successful indigenous lobbying and advocacy, as in the case of managing persistent organic pollutants and heavy metals in the Arctic (Selin and Selin, 2008).

12.3.3. Local and Traditional Forms of Knowledge

There is *high agreement* among researchers that involvement of local people and their local, traditional, or indigenous forms of knowledge in decision making is critical for ensuring their security (Ellemor, 2005; Kesavan and Swaminathan, 2006; Burningham et al., 2008; Mercer et al., 2009; Pearce et al., 2009; Anik and Khan, 2012). Such forms of knowledge include categories such as traditional ecological knowledge,

Frequently Asked Questions

FAQ 12.2 | Can lay knowledge of environmental risks help adaptation to climate change?

Lay knowledge about the environment and climate is deeply rooted in history, and encompasses important aspects of human life. Lay knowledge is particularly pertinent in cultures with an intimate relationship between people and the environment. For many indigenous and rural communities, for example, livelihood activities such as herding, hunting, fishing, or farming are directly connected to and dependent on climate and weather conditions. These communities thus have critical knowledge about dealing with environment changes and associated societal conditions. In regions around the world, such knowledge is commonly used in adapting to environmental conditions and is directly relevant to adaptation to climate change.

indigenous science, and ethnoscience (Nakashima and Roué, 2002). Collectively they are defined as "a cumulative body of knowledge, practice and belief, evolving by adaptive processes and handed down through generations" (Berkes, 2012, p. 7). In addition to reasserting culture, identity, and traditional values, such forms of knowledge are experiential, dynamic, and highly context dependent, developed through interactions with other forms of knowledge (Ford et al., 2006; Orlove et al., 2010; Sánchez-Cortés and Chavero, 2011; Eira et al., 2013).

The conclusion of many anthropological studies in this area is that there is *robust evidence* that mutual integration and co-production of local and traditional and scientific knowledge increase adaptive capacity and reduce vulnerability (Kofinas, 2002; Oberthür et al., 2004; Anderson et al., 2007; Tyler et al., 2007; Vogel et al., 2007; Marfai et al., 2008; West et al., 2008; Frazier et al., 2010; Armitage et al., 2011; Flint et al., 2011; Ravera et al., 2011; Nakashima et al., 2012; Eira et al., 2013). Local and traditional knowledge about historical changes and adaptation strategies are valuable for evaluating contemporary responses to environmental and social change and policy (Orlove et al., 2000; Desta and Coppock, 2004; Angassa and Oba, 2008; Ford et al., 2008; Lefale, 2010; Osbahr et al., 2010; Fernández-Giménez et al., 2012; Eira et al., 2013). Traditional knowledge contributes to mitigating the impact of natural disasters (Rautela, 2005), maintaining domestic biodiversity (Emperaire and Peroni, 2007) and developing sustainable adaptation and mitigation strategies (Nyong et al., 2007; Adler et al., 2013). A study of Borana indigenous pastoralists, for example, documented how loss of technical and organizational practices contributed to progressive land degradation, erosion of social structures, and poverty (Homann et al., 2008). Local and traditional knowledge is also applied in folk forecasting of weather and has been shown to be mutually reinforcing with scientific forecasts of weather at different time scales (Orlove et al., 2000; Nyong et al., 2007; Tyler et al., 2007; Gearheard et al., 2010; Hovelsrud and Smit, 2010).

Despite recognition in studies of the value of local and traditional knowledge, such knowledge is most often not included in adaptation planning (Tàbara et al., 2003; King et al., 2007; Ifejika Speranza et al., 2008; Huntington, 2011). There are many challenges in managing, utilizing, acknowledging, and incorporating local and traditional knowledge into adaptation practices (Huntington, 2011). Such knowledge is often generated and collected through participatory approaches, an approach that may not be sufficient because of the cultural and social dynamics of power and interpretation (Roncoli et al., 2011). Local and traditional knowledge itself may have its limits. Some studies suggest that local or traditional knowledge may not be sufficient to provide the proper response to unexpected or infrequent risks or events (Nunn, 2000; Burningham et al., 2008; Kuhlicke, 2010).

There is also concern, documented in many anthropological studies, that indigenous and traditional knowledge is itself under threat. If local or traditional knowledge is perceived to be less reliable because of changing environmental conditions (Ingram et al., 2002; Ford et al., 2006) or because of extreme or new events that are beyond the current local knowledge and cultural repertoire (Valdivia et al., 2010; Hovelsrud et al., 2010a), then community vulnerability, and the vulnerability of local or traditional knowledge itself, may increase (Kalanda-Joshua et al., 2011). New conditions may require new knowledge to facilitate and maintain flexibility and improve livelihoods (see also Homann et al., 2008). Kesavan and Swaminathan (2006) documented how societal and environmental conditions have changed to the point that local knowledge is supplemented with new technologies and new knowledge in coastal communities in India. A study in the Himalayas found that erosion of traditional knowledge occurs through government regulations of traditional building materials and practices (Rautela, 2005). The social cohesion embedded in such practices is weakened because of a move toward concrete construction which changes the reliance on and usefulness of traditional knowledge about wood as a building material (Rautela, 2005).

12.4. Migration and Mobility Dimensions of Human Security

12.4.1. Impacts of Climate Change on Displacement, Migration, and Mobility

12.4.1.1. Nature of Evidence on Climate Change and Migration

This section details how some existing migration systems may be significantly disrupted by impacts of climate change in a number of important dimensions. This finding comes from a very significant new body of observational and theoretical research in the past 5 years, as the migration and mobility dimensions of the impacts of climate change and the central role of mobility in adaptation have become apparent

(Afifi and Jäger, 2010; Foresight, 2011; Piguet et al., 2011). As with other elements of human security, the dynamics of the interaction of mobility with climate change are multifaceted and direct causation is difficult to establish.

The major findings of this emerging science demonstrate the multiple drivers of migration; show the role of displacement of populations from extreme weather events; and highlight the governance challenges of displaced peoples and the challenges of migration for urban sustainability (Black et al., 2011a,c; Foresight, 2011; Parnell and Walawege, 2011; Seto, 2011; White, G., 2011; Geddes et al., 2012). Studies have derived these findings through multiple methods and lines of evidence including statistical inference to explain observed migration patterns using climate or related impacts as independent variables; sample surveys of migrant motivations and behavior; modeling techniques; and historical analogs (McLeman and Hunter, 2010; Piguet, 2010; Warner, 2011; Oswald Spring et al., 2013; Warner and Afifi, 2013).

Migration in this chapter is defined in terms of temporal and spatial characteristics: it is a permanent or semi-permanent move by a person of at least one year that involves crossing an administrative, but not necessarily a national, border (Brown and Bean, 2005). Permanent migration, as well as temporary and seasonal migration, are prevalent in every part of the world, and are driven by economic and other imperatives. The most significant contemporary overall trend in migration continues to be major movements of people from rural to urban settlements. The proportion of the global population that is urban has risen from 10% in 1900 to more than 50% in 2009 and is projected to reach 59% by 2030 (Grimm et al., 2008). Around 80% of all migration is presently within countries (UNDP, 2009). Existing global migration trends mapped onto ecological zones by de Sherbinin et al. (2012) show that the past 4 decades have seen out-migration from mountain regions and from drylands. Net migration to coastal zones is estimated as having been more than 70 million people in the 1990–2000 census period.

12.4.1.2. Potential Pathways from Climate Change to Migration

Extreme weather events provide the most direct pathway from climate change to migration. It is widely established that extreme weather events displace populations in the short term because of their loss of place of residence or economic disruption. Only a proportion of displacement leads to more permanent migration (Foresight, 2011; Hallegatte, 2012). Much of the literature, such as reviewed in the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX), concludes that an increasing incidence and changing intensity of extreme weather events due to climate change will lead directly to the risk of increased levels of displacement.

The evidence on displacement as a result of weather-related events suggests that most displaced people attempt to return to their original residence and rebuild as soon as practical. The Pakistan floods of 2010, for example, caused primarily localized displacement for large numbers of people across a wide area (Gaurav et al., 2011), rather than longer-distance migration. Structural economic causes of social vulnerability may determine whether temporary displacement turns into permanent migration. In New Orleans, after Hurricane Katrina, for example, economically disadvantaged populations were displaced in the immediate aftermath and most have not returned (Myers et al., 2008; Mutter, 2010). Fussell et al. (2010) found that 14 months after the event, African American residents returned more slowly, because they had suffered greater housing damage. Studies conclude that displacement affected human security through housing, economic, and health outcomes and that these have perpetuated the initial impact into a chronic syndrome of insecurity (Adams et al., 2009; Hori and Shafer, 2010). Furthermore, there are well-documented gender differences in displacement from extreme events, especially when women lose their social networks or their social capital, and women are often affected by adverse mental health outcomes in situations of displacement (Tunstall et al., 2006; Oswald Spring, 2008; Hunter and David, 2011).

Therefore, extreme weather events are not necessarily associated with displacement and can also be associated with immobility or in-migration. Changing economic structures can shape the ability of affected populations to cope with extreme weather without being displaced. While the poorest households in Honduras suffered greatest losses due to the impacts of Hurricane Mitch in 1990 (Glantz and Jamison, 2000; McLeman and Hunter, 2010; McSweeney and Coomes, 2011), they were found to be less vulnerable to storms a decade later due to changes in land tenure and better early warning systems (Villagrán de León, 2009). Paul (2005) found that there was little displacement in Bangladesh following floods and that residents perceived an influx of migrants due to the reconstruction.

It is well established in demography that while migration is a common strategy to deal with livelihood risk, movement is costly and disruptive and hence may be used only as an adaptation of last resort (McLeman, 2009). Hurlimann and Dolnicar (2011) showed for eight Australian settlements experiencing long-term drought that relocation and migration was perceived to be the least desirable adaptation. Marshall et al. (2012) similarly showed that place attachment dominated decision making and reluctance to undertake relocation of farming communities. Haug (2002) showed that pastoralists displaced due to drought in Sudan in the 1990s attempted to return to their previous settlements after the drought, notwithstanding conflict and other factors. McLeman and Hunter (2010) reviewed historical cases of displacement migration and concluded that non-migration or rapid return significantly outweighs permanent migration following hurricane impacts in the Caribbean, Dust Bowl migration in the 1930s USA, or dry season migration in the West African Sahel.

A further strand of evidence shows social differentiation in access to the resources necessary to migrate influences migration outcomes (Renaud et al., 2011; Black et al., 2013). Vulnerability is inversely correlated with mobility, leading to those being most exposed and vulnerable to the impacts of climate change having the least capability to migrate (Figure 12-1). Therefore, climate change risks can be significant when they reduce and constrain opportunities to move (Black et al., 2013). Alternatively, the most vulnerable households are able to use migration to cope with environmental stress, but their migration is an emergency response that creates conditions of debt and increased vulnerability, rather than reducing them (Warner and Afifi, 2013). Table 12-3 summarizes studies on the migration outcomes of weather extremes and long-term environmental change. It shows that some events lead to increased

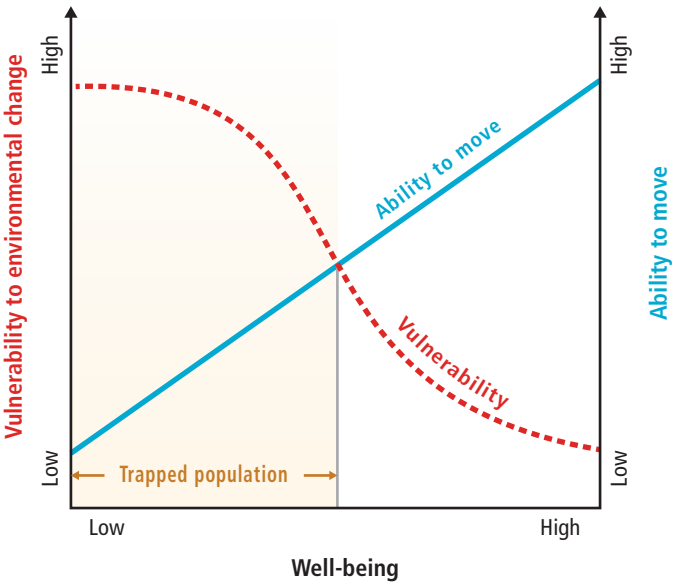


Figure 12-1 | Relationship between vulnerability to environmental change and mobility showing that populations most exposed and vulnerable to the impacts of climate change may have least ability to migrate (adapted from Foresight, 2011; Black et al., 2013).

displacement of populations, while others lead to reduced mobility. Table 12-3 also demonstrates that, in many circumstances, members of a population will display differentiated migration outcomes on the basis of ethnicity, wealth, or gender (Elliot and Pais, 2006; Gray and Mueller, 2012; Upton, 2012).

There is some evidence that climate changes, through impacts on productivity, can lead to reductions in migration flows. Studies in Table 12-3 highlight that some longer distance migration is reduced by drought in pastoral systems (Findley, 1994; van der Geest, 2011; Sánchez et al., 2013). Drought was also found to reduce migration in other systems. Henry et al. (2004) confirmed in a multiyear study of Burkina Faso that the movement to other rural areas increased in dry years, but long-distance or international migration was limited to years of high agricultural productivity. Pioneer migration to new destinations, long distance migration, and international migration all require significant human and financial capital and hence are restricted to wealthier populations or to time periods where the household has sufficient resources. However, in some contexts drought can lead to increased migration—often short-term and short-distance migration. Kniveton et al. (2011, 2012) modeled migration movements from the 1980s in Burkina Faso and project that future scenarios of decreased rainfall would increase rates of out-migration from rural areas.

Whether or not negative environmental change influences the decision to migrate, migrant populations may be exposed to more hazardous climatic conditions in their new destinations (Black et al., 2011b). There is some evidence that new migrants are more at risk in destination areas such as cities. Low-income migrants, as well as being socially excluded, cluster in high-density areas that are often highly exposed to flooding and landslides, with these risks increasing with climate change (Chatterjee, 2010; Fox and Beall, 2012; McMichael et al., 2012). Migrants in Buenos Aires, Lagos, Mumbai, and Dakar (Chatterjee, 2010; World Bank, 2010; Mehrotra et al., 2011) more often live in more hazardous locations than long-term residents. In Dakar, 40% of new migrants in the decade until 2008 resided in areas with high flood risk (World Bank, 2010). Wang et al. (2012) found that migrants had less knowledge about typhoon risks in Shanghai. Tompkins et al. (2009) showed that new migrants in the Cayman Islands are most vulnerable to tropical cyclones as they are least likely to prepare for cyclones, more likely to live in locations with high exposure to cyclone impacts, and interact mostly with expatriates without previous cyclone experience. There is no established evidence that rapid urbanization itself is a source of conflict: Buhaug and Urdal (2013) test hypotheses on social disorder and population growth in 55 cities in Africa and find that rapid growth of city populations does not drive urban unrest.

12.4.1.3. Migration Trends and Long-Term Climate Change

Long-term environmental change, sea level rise, coastal erosion, and loss of agricultural productivity (Table 12-3) will have a significant impact

Frequently Asked Questions

FAQ 12.3 | How many people could be displaced as a result of climate change?

Displacement is the movement of people from their place of residence, and can occur when extreme weather events, such as flood and drought, make areas temporarily uninhabitable. Major extreme weather events have in the past led to significant temporary population displacement, and changes in the incidence of extreme events will amplify the challenges and risks of such displacement. However, many vulnerable groups do not have the resources to be able to migrate from areas exposed to the risks from extreme events. There are no robust global estimates of future displacement, but there is significant evidence that planning and increased mobility can reduce the human security costs of displacement from extreme weather events. Climate changes in rural areas could amplify migration to urban centers. However, environmental conditions and altered ecosystem services are few among the many reasons why people migrate. So while climate change impacts will play a role in these decisions in the future, given the complex motivations for all migration decisions, it is difficult to categorize any individual as a climate migrant (Section 12.4).

Table 12-3 | Empirical evidence on observed or projected mobility outcomes (migration, immobility, or displacement) associated with weather-related extremes or impacts of longer-term climate change.

Type of impact or extreme	Change in migration trend or flow	Region	Impact on migration, by type of short-term event and long-term change	Source
Drought and land degradation	Evidence for increased mobility or increased displacement	Ethiopia	Outmigration of household heads due to drought-related famine. Different coping strategies lead to variations in the timing of migration.	Meze-Hausken (2000)
		Mexico	At the state level, a reduction in crop yields is associated with an increase in international migration to the United States.	Feng et al. (2010)
		Western Sahara	Environmental factors influenced decisions to migrate internationally from refugee camps.	Gila et al. (2011)
		Kenya	Households farming high-quality soil are less likely to migrate, especially for temporary labor; soil degradation therefore causes increased outmigration.	Gray (2011)
		India	Temporary migration is identified as "the most important" coping strategy in times of drought in rural villages.	Jülich (2011)
		Canada	Higher population loss was associated with settlements containing areas of poorer quality agricultural soils during droughts of 1930s.	McLeman and Ploeger (2012)
		Guatemala	Migrants to the expanding agricultural frontier commonly attributed their outmigration to soil degradation.	López-Carr (2012)
		Sahel	In three case regions, the pressure to migrate had significantly increased since the 1970s, with response to persistent droughts identified as a factor.	Scheffran et al. (2012b,d)
		Burkina Faso	Drier region populations were more likely to engage in rural–rural migration, both temporary and permanent, than people from regions with more rainfall. Rainfall deficits have different impacts depending on the duration and distance of the migration.	Henry et al. (2004)
		Burkina Faso[a]	Simulated scenarios of dry climate increase migration fluxes compared to wet scenarios. Highest international migrant flows are shown with the dry climate scenarios.	Kniveton et al. (2011)
	Evidence for decreased mobility	Mali	Reduced international migration occurred during the 1980s drought concurrently with an increase in localized cyclical migration.	Findley (1994)
		Nepal	Deforestation, population pressure, and agricultural decline leads to local mobility, especially among women, but no increases in internal or international migration.	Massey et al. (2010); Bohra-Mishra and Massey (2011)
		Uganda	High soil quality marginally increases migration, especially permanent non-labor migration; therefore soil degradation reduces outmigration.	Gray (2011)
	Evidence for socially differentiated mobility outcomes	United States	Dustbowl migrants from Oklahoma to California in the 1930s had different social and economic capital endowments from those who stayed within state.	McLeman and Smit (2006)
		Ecuador	Influence of natural capital on migration differed between men and women. Access to land facilitates migration in men; women are less likely to migrate from environmentally degraded areas.	Gray (2010)
		Ethiopia	Male migration increases with drought. However, marriage-related moves by women decrease with drought.	Gray and Mueller (2012)
		Burkina Faso	Labor migration became a key off-farm livelihood strategy after droughts in the 1970s for groups dependent on rain-fed agriculture.	Nielsen and Reenberg (2010)
		Mongolia	Diversity was seen in herders' mobility strategies in response to climate change. For a minority, responses entailed greater overall annual mobility. Other herding households experienced significant reductions in mobility.	Upton (2012)
Flooding	Evidence for increased mobility or increased displacement	United States	Ten counties and parishes in Louisiana, of the 77 impacted counties, experienced 82% of the total population increase in the year following Hurricane Katrina.	Frey and Singer (2006)
		Vietnam	Cumulative impacts of seasonal flooding increase outmigration rates in the Mekong Delta.	Dun (2011)
		Bangladesh	22% of households affected by tidal-surge floods, and 16% affected by riverbank erosion, moved to urban areas.	Foresight (2011)
	Evidence for decreased mobility or trapped populations	Bangladesh	No outmigration was detected after 2004 tornado in Bangladesh as a result of the effective distribution of disaster aid.	Paul (2005)
		Senegal	More than 40% of new migrant populations located in high risk flood zones in Dakar.	Foresight (2011)
	Evidence for socially differentiated mobility outcomes	United States	Emergency evacuation responses and return migration after Hurricane Katrina were highly differentiated by income, race, class, and ethnicity.	Elliott and Pais (2006); Falk et al. (2006); Landry et al. (2007)
		Bangladesh	Wide variation seen among groups in attitudes toward, and capabilities for, migration as an adaptation to the impact of cyclone Aila.	Kartiki (2011)

Continued next page →

on migration flows (Lilleor and Van den Broeck, 2011). The evidence in this area comes from simulation studies of future migration flows and permanent displacement. Barbieri et al. (2010) estimated emigration rates in Brazil from affected rural areas and found that de-population occurs with relatively modest rates of warming. In their scenarios the biggest increase in migration comes from productive agricultural areas that support a large labor force. In a separate study, Mendelsohn et al. (2007) concluded that in dryland Brazil urban migration is *very likely*

Table 12-3 (continued)

Type of impact or extreme	Change in migration trend or flow	Region	Impact on migration, by type of short-term event and long-term change	Source
Sea level rise	Evidence for increased mobility or increased displacement	United States	Relative sea level rise caused island depopulation in Maryland. Final abandonment was a result of the population falling below the threshold required to support local services.	Arenstam Gibbons and Nicholls (2006)
			Coastal villages in Alaska are affected by sea level rise and coastal erosion to the point where resettlement is the only viable adaptation.	Bronen (2010); Oliver-Smith (2011); Marino (2012)
		United States[a]	The impact of future sea level rise is projected to extend beyond the inundated counties through migration networks that link inland and coastal areas and their populations.	Curtis and Schneider (2011)
		Vanuatu	Contemporary example of whole village displacement was associated with inundation, both from sea level rise and tectonic movement on Torres Islands.	Ballu et al. (2011)
		Papua New Guinea	Communities on Bougainville are considering resettlement to the main island due to coastal erosion, land loss, saltwater inundation, and food insecurity.	Oliver-Smith (2011)
	Evidence for decreased mobility or lower migration	Tuvalu	On the island of Funafuti, surveyed residents emphasize place attachment as reasons for not migrating, and do not cite climate change as a reason to migrate.	Mortreux and Barnett (2009)

Note: [a]Study based on simulations or projections.

due to agricultural income loss. Longer term environmental change caused by climate change also amplifies existing trends such as rural to urban migration, though results diverge on the importance of climate change and resource scarcity in driving such trends. Modelling studies with future projections on Mexico-USA migration rates (Feng et al., 2009) and on Brazilian internal migration (Barbieri et al., 2010) show that projections of drying increase emigration in established migration routes and de-population of rural areas (Oswald Spring et al., 2013). Barrios et al. (2006) showed that observed rainfall declines in areas of sub-Saharan Africa explain part of the differences in urbanization rates across countries, with periods of rainfall decline increasing urbanization in sub-Saharan Africa, but the urbanization is also explained by simultaneous economic liberalization and policy change.

Sea level changes have been projected to lead to permanent displacements as coastal areas become uninhabitable. Curtis and Schneider (2011), for example, project 12 million people to be displaced by sea level rise by 2030 in four major coastal areas in the USA. Nicholls et al. (2011) estimate permanent displacements based on potential sea level changes until 2100 (see Section 5.5.7). A 0.5 m sea level change implies a *likely* land loss of 0.877 million km^2 by 2100, displacing 72 million people, with no adaptation investment; with a 2.0 m sea level change, 1.789 million km^2 would be lost, displacing 187 million people, or 2.4% of global population, mostly in Asia. If governments undertook adaptation investments in all coasts (e.g., building protective dikes), then the study suggests very low levels of people displaced under the 0.5 m scenario and a population of less than half a million displaced under the 2.0 m sea level rise scenario (Nicholls et al., 2011). Hallegatte et al. (2011) and Seto (2011) show that such protection measures are *very likely* to be implemented because of the high cost of not investing in protecting urban land and infrastructure, especially for major urban centers.

Even in areas under threat from long-term climate change and sea level rise, observations show that populations at risk do not always choose to migrate. For example, a series of studies have sought to explain population stability in low-lying island nations. Mortreux and Barnett (2009) found that migration from Tuvalu was not driven by perceptions of climate change and that, despite forecasts that the island could become uninhabitable, residents have remained for reasons of culture and identity. Shen and Gemenne (2011) concur that both Tuvalu residents and migrants from Tuvalu did not cite climate change as a reason for the migration that occurs. Similarly, in the Peruvian Andes, Adams and Adger (2013) found that cultural ecosystem services and place attachment shape decisions not to migrate and hence populations persist despite difficult environmental conditions. However, these studies also find that environmental risks directly affect perceptions of well-being, cultural integrity, and economic opportunities. They conclude that the impacts of climate change may be a more significant driver of migration in the future.

12.4.2. Migration as an Adaptation to Climate Change Impacts

Migration is a widely used adaptation strategy that reduces risks in highly vulnerable places, as demonstrated by a wide range of studies. Research drawing on experience of migration policy concludes that a greater emphasis on mobility within adaptation policies would be

Frequently Asked Questions

FAQ 12.4 | What role does migration play in adaptation to climate change, particularly in vulnerable regions?

Moving from one place to another is a fundamental way humans respond to challenging conditions. Migration patterns everywhere are primarily driven by economic factors: the dominant migration system in the world has been movement from rural to urban areas within countries as people seek more favorable work and living conditions.

Box 12-4 | Evidence on the Existence of Environmental Migrants and International Policy for Their Protection

There is widespread agreement in the scientific and legal literature that the use of the term climate refugee is scientifically and legally problematic (Tacoli, 2009; Piguet, 2010; Black et al., 2011a; Gemenne, 2011; Jakobeit and Methmann, 2012; Bettini, 2013; Piguet, 2013). McAdam calls the concept "erroneous as a matter of law and conceptually inaccurate" (McAdam, 2011, p. 102). The reasons are threefold. First, most migration and climate studies point to the environment as triggers and not causes for migration decisions. Second, some studies focus on the negative geo-political implications of changing the Geneva Convention on refugees to include environmental migrants as well as the lack of global instruments to handle internal displaced peoples or international migrants (Martin, 2009; Cournil, 2011). Third, many Small Island States are reluctant themselves to have their international migrants designated as being victims of climate change (McNamara and Gibson, 2009; Farbotko, 2010; Barnett and O'Neill, 2012; Farbotko and Lazrus, 2012).

The arguments put forward for a specific legal instrument to deal with migrants who have been displaced as a direct result of climate change impacts include issues of rights, given such migration is imposed and involuntary (Bates, 2002; Bell, 2004); and the particular status of Small Island States where displacement could affect sovereignty (Biermann and Boas, 2008; Owens, 2008; Williams, 2008). For international displacement and migration, there is a growing literature on practical adaptation and action: the existence of governance mechanisms to improve handling of currently displaced people, and the optimal design of such mechanisms in the future (e.g., Bryavan and Rajan, 2006; Biermann and Boas, 2008; Williams, 2008; Docherty and Giannini, 2009; Martin, 2009; McAdam, 2011). This literature focuses on strategies for adaptation, mitigation, and resilience building, and concludes that significant adaptation may be required to protect and to empower internally or international migrants triggered by climate change.

effective when undertaken in a sensitive manner (Bardsley and Hugo, 2010; Barnett and Webber, 2010; Warner, 2010; Gemenne, 2011). This emerging literature shows that migration can be promoted to reduce risk successfully, not least through remittance flows between sending and destination areas (Deshingker, 2012; Fox and Beall, 2012; Martin, 2012). The prospect of migration as an effective adaptation is recognized through its inclusion in the Cancun Accord of the UN Framework Convention on Climate Change (Warner, 2012).

Various governments are presently engaged in planning to move settlements as part of adaptation strategies, either because of the assessment of new risks or to justify existing resettlement programs (de Sherbinin et al., 2011; Biermann, 2012). Scientific literature on these policies most often portrays resettlement as a failure of adaptation and a policy of last resort (Barnett and Webber, 2010; Fernando et al., 2010; Hugo, 2011). Most practice to date, learning from other resettlement programs, demonstrates negative social outcomes for those resettled, often analyzed as breaches in individual human rights (Bronen, 2011; Johnson, 2012; Arnall, 2013). There are some documented examples of settlements that are already planning for their own relocation, such as five indigenous communities in Alaska that have experienced increased erosion, loss of sea ice cover, and flooding over the past decades (Bronen, 2010). These settlements have undertaken planning for relocation and have received government funding for these processes. Bronen (2010) and Bronen and Chapin (2013) conclude that while the relocations are feasible, there are significant perceptions of cultural loss and related studies report psychological stress and community dislocation (Cunsolo-Wilcox et al., 2012, 2013). The studies argue that legitimacy and success depend on incorporating cultural and psychological factors in the planning processes (Bronen and Chapin, 2013). There is significant resistance to relocation, even where such options are well planned and have robust justifications, as demonstrated by Marino (2012) for relocation in Alaska.

12.5. Climate Change and Armed Conflict

12.5.1. Climate Change as a Cause of Conflict

In the past decade there has been a marked increase in research investigating the relationship between climate change and violent and armed conflict. This section assesses the full spectrum of research using diverse methods and data to understand the relationship between climate change and armed conflict. Chapter 19 provides a more detailed assessment of those studies that seek to quantify the influence of climate factors on violence of all kinds, including personal violence. Chapter 19 defines the influence of climate impacts on violence to be an emergent risk and a new focus of research. In this chapter, armed conflicts are defined as those conflicts that involve more than 25 battle-related deaths in a year. This can include interstate conflicts, intrastate conflicts that involve governments, non-state conflicts in which governments are not directly involved, and one-sided conflicts involving organized violence against civilians (Themnér and Wallensteen, 2012).

There is a specific research field that explores the relationship between large-scale disruptions in climate and the collapse of past empires.

Frequently Asked Questions

FAQ 12.5 | Will climate change cause war between countries?

Climate change has the potential to increase rivalry between countries over shared resources. For example, there is concern about rivalry over changing access to the resources in the Arctic and in transboundary river basins. Climate changes represent a challenge to the effectiveness of the diverse institutions that already exist to manage relations over these resources. However, there is high scientific agreement that this increased rivalry is unlikely to lead directly to warfare between states. The evidence to date shows that the nature of resources such as transboundary water and a range of conflict resolution institutions have been able to resolve rivalries in ways that avoid violent conflict.

Relationships are explored using statistical analysis and data derived from archaeological and other historical records. For example, the timing of the collapse of the Khmer empire in the Mekong basin in the early 15th century corresponds to an unusually severe prolonged drought (Buckley et al., 2010). DeMenocal (2001) summarizes evidence that suggests that major changes in weather patterns coincided with the collapse of several previously powerful civilizations, including the Anasazi, the Akkadian, Classic Maya, Mochica, and Tiwanaku empires. Other historical reference points of the interaction of climate with society emerge from analysis of the Little Ice Age. Some studies show that the Little Ice Age in the mid-17th century was associated with more cases of political upheaval and warfare than in any other period (Parker, 2008; Zhang et al., 2011), including in Europe (Tol and Wagner, 2010), China (Brook, 2010), and the Ottoman empire (White, S., 2011). These studies all show that climate change can exacerbate major political changes given certain social conditions, including a predominance of subsistence producers, conflict over territory, and autocratic systems of government with limited power in peripheral regions. The precise causal pathways that link these changes in climate to changes in civilizations are not well understood due to data limitations. Therefore, it should be noted that these findings from historical antecedents are not directly transferable to the contemporary globalized world. The literature urges caution in concluding that mean future changes in climate will lead to large-scale political collapse (Butzer, 2012).

Most of the research on the connections between climate change and armed conflict focuses on the connections between climate variability and intrastate conflicts in the modern era. For the most part, this research examines rainfall or temperature variability as proxies for the kinds of longer-term changes that might occur due to climate change. Several studies examine the relationship between short-term warming and armed conflict (Burke et al., 2009; Buhaug 2010; Koubi et al., 2012; O'Loughlin et al., 2012; Theisen et al., 2012). Some of these find a weak relationship, some find no relationship, and collectively the research does not conclude that there is a strong positive relationship between warming and armed conflict (Theisen et al., 2013).

The large majority of studies focuses on Africa and use satellite-enhanced rainfall data collected since 1980. A global study by Hsiang et al. (2011) considers changes in climate over multiple years, and finds that since 1950 and in countries that are affected by El Niño-Southern Oscillation (ENSO) the risk of war within countries rises during an ENSO period. This study is supported by some studies that find associations between deviations in rainfall and civil war (Miguel et al., 2004; Hendrix and Glaser, 2007; Hendrix and Salehyan, 2012; Raleigh and Kniveton, 2012), but contradicted by others that find no significant association between droughts and floods and civil war (Buhaug, 2010; Buhaug and Theisen, 2012; Koubi et al., 2012; Slettebak, 2012; Theisen et al., 2013). There is *high agreement* that in the specific circumstances where other risk factors are extremely low (such as where per capita incomes are high, and states are effective and consistent), the impact of changes in climate on armed conflict is negligible (Bernauer et al., 2012; Koubi et al., 2012; Scheffran et al., 2012a; Theisen et al., 2013).

A growing body of research examines the connections between climate variability and non-state conflicts. There is some agreement that either increased rainfall or decreased rainfall in resource-dependent economies enhances the risk of localized violent conflict, particularly in pastoral societies in Africa (Benjaminsen and Ba, 2009; Benjaminsen et al., 2009; Adano et al., 2012; Butler and Gates, 2012; Fjelde and von Uexkull, 2012; Hendrix and Salehyan, 2012; Raleigh and Kniveton, 2012; Theisen, 2012). In all such cases, the presence of institutions that are able to peacefully manage conflict are highlighted as the critical factor in mediating such risks (Gausset, 2005; Hidalgo et al., 2010; Adano et al., 2012; Benjaminsen et al., 2012; Butler and Gates, 2012; O'Loughlin et al., 2012; Theisen, 2012).

In response to the challenges of finding direct associations between changes in climate and violence, some research has examined the effects of changes in climate on factors that are known to increase the risk of civil war (Bergholt and Lujala, 2012; Koubi et al., 2012). Civil war has been studied extensively using quantitative and qualitative techniques, and there is *high agreement* about factors that increase the risk of civil war, namely a recent history of civil violence, low levels of per capita income, low rates of economic growth, economic shocks, inconsistent political institutions, and the existence of conflict in neighboring countries (Miguel et al., 2004; Weede, 2004; Hegre and Sambanis, 2006; Dixon, 2009; Blattman and Miguel, 2010; Brückner and Ciccone, 2010). Nevertheless, almost all studies note the need for convincing theories that explain these associations.

Many of the factors that increase the risk of civil war and other armed conflicts are sensitive to climate change. For example, Chapter 10 shows that climate change will slow rates of economic growth and impede efforts to grow per capita incomes in some low-income countries, particularly in Africa where the risk of conflict is highest (Mendelsohn

Box 12-5 | Climate and the Multiple Causes of Conflict in Darfur

Climate variability or climate change is popularly reported to be significant causes of the mass killing in the Darfur region that began in 2003 (see Mazo, 2009). Five detailed studies dispute the identification of the Darfur conflict as being primarily caused by climate change (Kevane and Gray, 2008; Brown, 2010; Hagen and Kaiser, 2011; Sunga, 2011; Verhoeven, 2011). They find that the violence in Darfur has multiple causes, notably:

- The legacy of past violence, which established groups that had a history of violent action and a supply of weapons
- Manipulation of ethnic divisions by elites in Khartoum
- Weakening of traditional conflict resolution mechanisms through government policies and as a consequence of famines
- Systematic exclusion of local groups from political processes, including of the Fur, Masalit, and Zaghawa ethnic groups
- Limited economic development and inadequate provision of public services and social protection, stemming from governance and policy failures, political instability, and misuse of official development assistance.

All studies of this conflict agree that it is not possible to isolate any of these specific causes as being most influential (Kevane and Gray, 2008; Hagen and Kaiser, 2011; Sunga, 2011; Verhoeven, 2011). Most authors identify government practices as being far more influential drivers than climate variability, noting also that similar changes in climate did not stimulate conflicts of the same magnitude in neighboring regions, and that in the past people in Darfur were able to cope with climate variability in ways that avoided large-scale violence.

et al., 2000, 2006, Stern, 2007, Eboli et al., 2010). Extreme events, which may become more intense due to climate change, can also produce economic shocks (Bergholt and Lujala, 2012; Hallegatte, 2012; Adam, 2013), although the direct association between disasters and armed conflict is contested (Pelling and Dill, 2010; Bergholt and Lujala, 2012; Slettebak, 2012). Studies have inferred that climate change can undermine the consistency of institutions that provide public goods (Barnett and Adger, 2007; Scheffran et al., 2012b) and hence weaken states and increase conflict risks. However, there is some evidence that, under certain circumstances, disasters can provide critical opportunities to build peace in conflict settings and to improve governance institutions (Kingsbury, 2007; Olson and Gawronski, 2010; Bruckner and Ciccone, 2011).

In summary, there is justifiable common concern that climate change or changes in climate variability increase the risk of armed conflict in certain circumstances (Bernauer et al., 2012; Gleditsch, 2012; Scheffran et al., 2012c; Hsiang et al., 2013), even if the strength of the effect is uncertain. This concern is justified given robust knowledge of the factors that increase the risk of civil wars, and medium evidence that some of these factors are sensitive to climate change.

There is also general agreement in the literature that there is a need for theories and data that explain the processes that lead from changes in climate to violence—for example, on how formal and informal institutions help avoid violent outcomes (Barnett and Adger, 2007; Scheffran and Battaglini, 2011; Buhaug and Theisen, 2012, Gleditsch, 2012; Murtinho and Hayes, 2012). Confident statements about the effects of future changes in climate on armed conflict are not possible given the absence of generally supported theories and evidence about causality (see Box 12-5).

12.5.2. Conflict and Insecurity Associated with Climate Policy Responses

Research is beginning to show that climate change mitigation and adaptation actions can increase the risk of armed conflict, as well as compound vulnerabilities in certain populations (Bumpus and Liverman, 2008; Adger and Barnett, 2009; Webersik, 2010; Fairhead et al., 2012; Marino and Ribot, 2012; Steinbruner et al., 2012). This is based on robust evidence that violent political struggles occur over the distribution of benefits from natural resources (Peluso and Watts, 2001). Hence, in circumstances where property rights and conflict management institutions are ineffective or illegitimate, efforts to mitigate or adapt to climate change that change the distribution of access to resources have the potential to create and aggravate conflict.

Actions taken in response to climate change can aggravate existing significant inequalities or grievances over resources (Marino and Ribot, 2012), limit access to land and other resources required to maintain livelihoods, or otherwise undermine critical aspects of human security (Bumpus and Liverman, 2008; Fairhead et al., 2012). Maladaptation or greenhouse gas mitigation efforts at odds with local priorities and property rights may increase the risk of conflict in populations, particularly where institutions governing access to property are weak, or favor one group over another (Barnett and O'Neill, 2010; Butler and Gates, 2012; McEvoy and Wilder, 2012). Research on the rapid expansion of biofuels production connects land grabbing, land dispossession, and social conflict (Borras et al., 2010; Dauverge and Neville, 2010; Molony and Smith, 2010; Vermeulen and Cotula, 2010). One study has identified possible links between increased biofuels production, food price spikes, and social instability such as riots (Johnstone and Mazo, 2011).

Provision of financial resources in payment for ecosystem services projects, such as are associated with Reduced Emissions from Deforestation and Forest Degradation (REDD), has the potential to stimulate conflict over resources and property rights (Melick, 2010). For example, efforts to ensure "REDD readiness" in Tanzania (Beymer-Farris and Bassett, 2012, 2013; Burgess et al., 2013) and the Congo basin (Brown et al., 2011) have been contested, and placed communities in conflict with conservationists and governments. Eriksen and Lind (2009) similarly find that climate change adaptation interventions in Kenya have aggravated surrounding conflicts.

Climate change mitigation will increase demand for deployment of less carbon-intensive forms of energy, including hydropower, some of which have historically resulted in social conflict and human insecurity (e.g., because of forced resettlement), and this is a basis for concern about increased violence and insecurity in the future (Conca, 2005; McDonald-Wilmsen and Webber, 2010; De Sherbinin et al., 2011). Other research points to an increased use of nuclear power increasing the threat of nuclear proliferation or incidents of nuclear terrorism (Socolow and Glaser, 2009, Steinbruner et al., 2012). Climate policy responses also have the potential to reduce conflict in various ways, as explained further in Section 12.5.4.

12.5.3. Violent Conflict and Vulnerability to Climate Change

Many of the capacities required to adapt to climate change are threatened by ongoing or recent armed conflict (Barnett, 2006; Brklacich et al., 2010). There is a strong body of evidence from development studies and political science that violent conflict undermines human security and the capacity of individuals, communities, and states to cope with changes (Stewart and Fitzgerald, 2001; Blattman and Miguel, 2010). These observations suggest, with *high confidence*, that where violent conflict emerges and persists the capacity to adapt to climate change is reduced for affected populations. This is illustrated in Figure 12-2 which shows that post-conflict societies have low adaptive capacity, where human development acts as a proxy for adaptive capacity (Barnett, 2006; Lind and Eriksen, 2006; Eriksen and Lind, 2009; Adger, 2010).

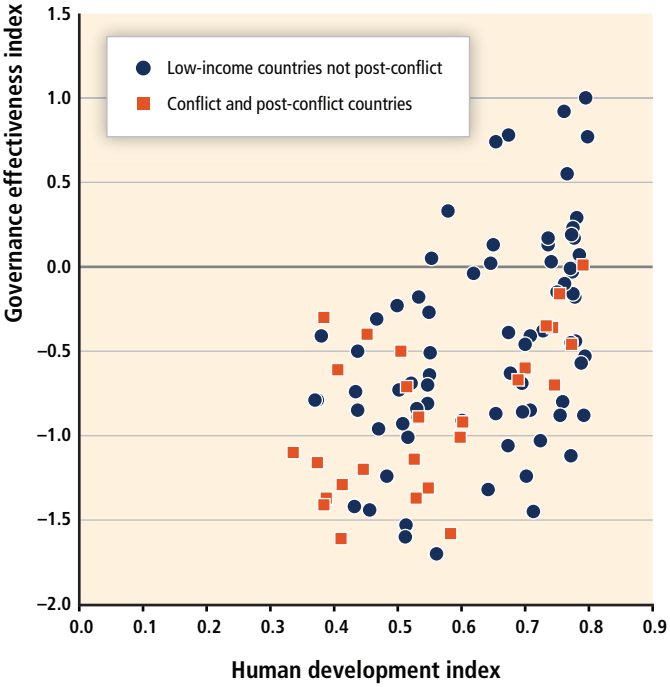


Figure 12-2 | Conflict and post-conflict societies exhibit low levels of governance and human development. Data based on UNDP Human Development Index and World Bank index on governance effectiveness (adapted from Adger, 2010).

Armed conflict disrupts markets and destroys infrastructure, limits education and the development of human capital, causes death and injury to workers, and decreases the ability of individuals, communities, and the state to secure credit (Stewart et al., 2001; Goodhand, 2003; Blattman and Miguel, 2010). Conflict thus creates poverty and constrains livelihoods that, in turn, increases vulnerability to the impacts of climate change (Nigel, 2009; Deng, 2010a; Hilson and van Bockstael, 2011). Violent conflict is a major cause of hunger and famines (de Waal, 1993; Messer and Cohen, 2011; Rowhani et al., 2011). Armed conflict interrupts the ability of resource-dependent individuals and communities to access natural resources (Pike, 2004; Detraz, 2009; Kolmannskog, 2010; Raleigh, 2011), and in so doing limits their capacity to adapt to climate change. The denial of strategic space as a tactic in armed conflict (through, e.g., deliberate destruction of crops and spreading of landmines in conflict affected regions) can reduce the capacity of individuals and communities to access natural capital and hence cope with climate variability (Berhe, 2007; Unruh, 2012).

A parallel body of research documents negative feedbacks on adaptive capacity where armed conflict reduces access to ecosystem goods and services, which can lead to inefficient use of natural resources and hence to further environmental degradation. Chronic political instability in Zimbabwe is, for example, implicated in high levels of illegal bush meat hunting (Lindsey et al., 2011). Conflict, and the displacement of large populations, can also alter the abundance and distribution of biodiversity and can result in significant deforestation (Chase and Griffin, 2011; Lindsell et al., 2011; Stevens et al., 2011).

The capacity for collective action is a critical determinant of the capacity to adapt to climate impacts, and this too can be undermined by violent conflict, depending on the nature of violence and the strategies households adopt in response (Deng, 2008, 2010b). When conflict exacerbates existing horizontal inequalities between ethnic or religious groups, foments distrust in local or government institutions, or isolates individuals and households, the social capital that is important for adapting to climate change is also degraded (Bogale and Korf, 2007). Conflict-related displacement also disrupts social networks and makes it difficult to achieve elements of secure livelihoods, such as marriage, access to land, or access to communal social safety nets (Kolmannskog, 2010; Raleigh, 2011). In situations of violent conflict, efforts to address climate change that provide financial or resource flows that can be captured by local elites or illegitimate institutions may compound divisions and exacerbate grievances (Brown et al., 2011; Verhoeven, 2011).

Armed conflict can decrease the capacity of governments to function effectively, which in turn impedes adaptation (Tignino, 2011; Feitelson et al., 2012). For example, research has shown that chronic political conflict has reduced the ability of governance institutions at many scales

to effectively manage water resources in the Gaza Strip (Shomar, 2011), parts of the Balkans (Skoulikidis, 2009), and the Middle East (Zeitoun et al., 2012). Instability has affected planning processes around urban land use in Palestine (Raddad et al., 2010) and in regions of Iraq (Hassan, 2010). Armed conflict may also undermine the ability of states to prevent and respond to natural disasters and humanitarian crisis (Keen, 2008). A lack of trust in government commitment or capacity to respond, the presence of police or military forces that lack legitimacy, or recent conflict between government and local forces hampers the ability of these institutions to provide effective relief (Wisner, 2001).

12.5.4. Peace-Building Activities in Promoting Adaptation

In situations where conflict is resources based, it is widely established that resource management has significant potential to contribute to conflict management by channeling competing interests over resources into non-violent resolutions (Conca and Dabelko, 2002; Conca and Wallace, 2009; Lujala and Rustad, 2011; Jensen and Lonergan, 2013). This research on environmental peacebuilding and peacemaking considers that natural resource management, and by extension climate change adaptation, can help build peace to avoid conflicts, and broker peace in conflict situations (Tänzler et al., 2010).

Research on bilateral and multilateral interactions between two or more states from 1948 to 2008 shows strong evidence of significant formal cooperation among river basin riparian states, and no cases of water causing two states to engage in war (Wolf et al., 2003; Wolf, 2007; De Stefano et al., 2010). Transboundary water cooperation, particularly joint management, flood control, and technical cooperation, can form a basis for longer-term cooperation on a range of contentious issues. Efforts at basin-wide institutional development to lower conflict potential focuses on moving from the assertion of conflicting rights to water, to addressing the multiple values of water, and ultimately to sharing benefits across national boundaries (Sadoff and Grey, 2002).

There is an emerging body of evidence about the effectiveness of efforts to enhance cooperation and lower conflict around natural resources (Lujala and Rustad, 2011; Jensen and Lonergan, 2013). Some transboundary conservation areas, referred to as "peace parks," are designed to reduce conflict and enhance cooperation across borders. However, the evidence of the effectiveness of peace parks is limited and ambiguous, with some studies documenting political, economic, and conservation cooperation (Ali and Marton-LaFevre, 2007), while others document conflict generation between local communities, elites, and states (Duffy, 2002).

12.6. State Integrity and Geopolitical Rivalry

Climate change will affect the integrity of states through impacts on critical infrastructure, threats to territorial integrity, and geopolitical rivalry (Gilman et al., 2011). These impacts on infrastructure and geopolitical dimensions directly affect state capacities to provide a range of ecological, economic, social, and political services that fundamentally contribute to human security (Barnett, 2003; Busby, 2008; Barnett et al., 2010; Webersik, 2010).

12.6.1. Critical Infrastructure and State Capacity

Climate change and extreme events are projected to damage a range of critical infrastructure, with water and sanitation, energy, and transportation infrastructure being particularly vulnerable (Rozenzweig et al., 2011; UN-HABITAT, 2011; see also Section 8.2.4). Climate change is expected to exacerbate water supply problems in some urban areas that in turn pose multiple risks to cities. For example, the high-temperature and low-rainfall events that can cause a decline in the supply of water to cool power plants are those that simultaneously increase energy demand for cooling, threatening to disrupt power supply and communications technology. In areas where there may be flooding or increased snow and ice storms, critical infrastructure may be damaged (see Section 8.2.3). Areas that are vulnerable to flooding, landslides, or forest fires will have greater risk of such infrastructure damage (Revi, 2005; Awuor et al., 2008; Adelekan, 2010; Keywood et al., 2013).

Climate change impacts on critical infrastructure will reduce the ability of some states to provide social and public services (see Section 8.2.4.6). For example, power outages stemming from water shortages or storms can in turn lead to reductions in service delivery from hospitals, police forces, and emergency responders. Damage to roads, rails, airports, bridges, and related transport infrastructure can similarly reduce the ability of governments to provide for citizen needs. The impact of thawing permafrost on infrastructure will affect the viability of settlements in high latitudes (Larsen et al., 2008; Dersken et al., 2012; Marino, 2012; see also Sections 28.2.4.2, 28.3.4.3). In countries that are poor or that depend heavily on climate-sensitive activities such as agriculture, climate impacts are expected to lead to significant declines in income and, in turn, government revenues. Mideksa (2010) estimates that climate change impacts will reduce Ethiopia's gross domestic product (GDP) by nearly 10%.

12.6.2. Geopolitical Issues

Analysis of the actions of states and security institutions show that many states view current and anticipated climate changes as contributing to geopolitical concerns (Dabelko, 2009; Smith, 2011). The ability of states to share resources and provide human security is challenged by climate change impacts. Climate change impacts can create contested claims to territory on land and at sea and, in extreme cases, can threaten the territorial integrity or viability of states (Barnett and Campbell, 2010; Houghton et al., 2010; Yamamoto and Esteban, 2010).

For Small Island States and countries with significant areas of soft low-lying coasts (Hanson et al., 2011), sea level rise and extreme events threaten to erode and subsume significant land areas and associated infrastructure and settlements, in the absence of significant adaptation (Nicholls et al., 2011; see also Section 5.4.3.2). For countries made up entirely of low-lying atolls, sea level rise, ocean acidification, and increases in episodes of extreme sea surface temperatures compromise human security for present or future higher populations (Barnett and Campbell, 2010; Fisher, 2011). With projected high levels of sea level rise beyond the end of this century, the physical integrity of low-lying islands is under threat (Barnett and Adger, 2003; Houghton et al., 2010; Section 29.3). The opening of resources, such as the loss of sea ice in

Box 12-6 | Evidence on Security and Geopolitical Dimensions of Climate Change Impacts in the Arctic

Impacts of climate change on the Arctic region exemplify the multiple interactions of human security with geopolitical risks. System-wide changes in the Arctic region affect multiple countries and a global commons resource given Arctic roles in regulating the global climate and ocean systems (Carmack et al., 2012; Duarte et al., 2012). Anticipated changes will contribute to greater geopolitical considerations and human insecurity in the Arctic region. They include food insecurity affecting specific cultures and knowledge systems (outlined in Section 12.3); energy security implications through opening of sub-sea oil and gas reserves; increased shipping; increased pollution; search and rescue challenges; and increased military presence in the region.

The Arctic has been warming at about twice the global rate since 1980, resulting in unprecedented loss in sea ice. The Arctic Ocean is projected to experience major reductions in sea ice, and under some projections would be ice-free by the end of the century (WGI AR5 SPM, *medium confidence*; see also Section 28.1). These changes have implications for land-based infrastructure, shipping, resource extraction, coastal communities, and transport (Holland et al., 2006; Larsen et al., 2008; Stephenson et al., 2011; see also Section 28.3.4). There is *medium evidence* that changes will create or revive terrestrial and maritime boundary disputes among Arctic countries (Borgerson, 2008; Ebinger and Zambetakis, 2009; Lusthaus, 2010). There is little evidence the changing Arctic will become a site for violent conflict between states (Young, 2009; Berkman, 2010; Brosnan et al., 2011). At present, political institutions are providing forums for managing resource competition, new transportation practices, and boundary disputes, but anticipated increased stresses will test these institutions in the future (Ebinger and Zambetakis, 2009).

the Arctic and associated social, economic, and political dimensions (Section 28.2.5), represents an example of climate change impacts being geopolitically significant to states, even in the absence of direct conflict (Box 12-6). Expected sea level rise and resulting coastline changes may affect the location of Exclusive Economic Zones and contribute to conflicts over natural resources or boundary locations (Houghton et al., 2010).

Productive ocean fisheries are already directly affected by climate change, altering the range of important commercial fish stocks (MacNeil et al., 2010). Fishing, as an economic activity, is adapted to highly variable environmental and management conditions; however, the movement of fish stocks (see Section 6.3.2; Berkes et al., 2006) has been suggested to increase transboundary rivalry (MacNeil et al., 2010). For example, northward shifts of mackerel, herring, and capelin stocks are creating economic and geopolitical tension (Sumaila et al., 2011).

The impacts of climate-induced water variability on transboundary water basins constitute a cluster of geopolitical concerns. The high levels of international interdependence on transboundary rivers such as the Nile, Limpopo, Amu Darya, Syr Darya, Mekong, Ganges, Brahmaputra, Tigris, Euphrates, and Indus connect the conditions of the rivers with national development trajectories. Climate change is expected to disrupt the dynamics of runoff (*robust evidence*, *high agreement*; see Section 3.4.5). Warming, for example, will bring forward the snow melt season in all but the coldest regions, altering seasonal water flows (see Section 3.4.5). Such projections have led to concerns over transboundary tensions, particularly where challenges stemming from rising consumption and growing populations are already present (National Research Council, 2012; Swain, 2012).

Research on transboundary conflict and cooperation prioritizes rate of change rather than absolute scarcity in connection with the risk of conflict over water, particularly between states (De Stefano et al., 2012). This focus stems from higher perceived risk of conflict when institutions at local, state, and regional levels have less time to adapt to scarcity or variability by dealing with disputes through diplomatic and other non-violent mechanisms (Wolf et al., 2003; Wolf, 2007; De Stefano et al., 2010, 2012). Sudden changes in flow that heighten risk and challenge institutional responses include declines in seasonal snow or glacial melt. Transboundary basin institutions and international legal mechanisms have demonstrated an ability to manage conflict effectively (Sadoff and Grey, 2002; Wolf, 2007; Brochmann and Hensel, 2009; Dellapenna and Gupta, 2009; Goulden et al., 2009; Dinar et al., 2011; Bernauer and Siegfried, 2012; Feitelson et al., 2012; Gartzke, 2012; Tir and Stinnett, 2012). Other research emphasizes that these transboundary water institutions receive limited financial and political investment, involve unequal or inequitable cooperation between powerful and less powerful countries, and are present in only a limited number of transboundary basins (Conca et al., 2006; Zeitoun and Warner, 2006; Zeitoun and Mirumachi, 2008).

Geoengineering that involves deliberate large-scale manipulation of the environment aimed at reducing negative climate change impacts (Section 20.3) remains an unproven strategy to address climate change. The high levels of uncertainty and high likelihood of differential geographic impacts of geoengineering are anticipated sources of tension or conflict between states (Robock, 2008; Dalby, 2013; Preston, 2013). These include regional effects of solar radiation management on reduced precipitation in specific areas in Asia or in the Sahel (Ricke et al., 2010; Haywood et al., 2013) with negative food production implications. The ability of

states to deploy geoengineering unilaterally under limited international legal mechanisms creates the potential for conflict. Examples of security institutions attempting weather modification present the prospect of military involvement in deploying or interdicting geoengineering efforts (Fleming, 2010). The prospect for the securitization of geoengineering responses is contested: geoengineering technologies could be used for hostile purposes but the significance of this possibility is contested (Keith, 2000; Robock, 2008; Corner and Pidgeon, 2010; Brzoska, 2012).

12.7. Synthesis

This chapter shows that climate change and climate variability pose risks to various dimensions of human security, which arise through diverse causal processes and which will be manifest at different scales. There is *high agreement* in the literature for this conclusion that comes from multiple lines of evidence. There are, however, multiple and competing perspectives on the nature and causes of insecurity arising from climate change. For example, farmers in the Sahel are concerned about the risks weather extremes pose to their livelihoods (Mertz et al., 2009), whereas people in Tuvalu report that the cultural impacts of migration are a primary concern rather than climate change directly (Mortreux and Barnett, 2009). Organizations whose mandates include aspects of human security prioritize some risks of climate change over others in line with organizational priorities. For example, the International Organization for Migration is concerned with the implications of climate change for migration, and the U.S. National Intelligence Council is focused on the risk that climate change will increase political instability and geopolitical rivalry. In this respect the framing of climate change as an issue of human security enables conversations across the boundaries of diverse policy communities (Gasper, 2010).

The risks that climate change poses to human security arise through multiple and interacting processes. Those processes also operate across diverse spatial and temporal scales. High levels of complexity mean that no conceptual model or theory captures the full extent of the interactions between all of climate change, livelihoods, culture, migration, and violent conflict. However, as this chapter has shown, there are feedbacks between the key elements of livelihoods, culture, migration, and violent conflict. Figure 12-3 depicts one scenario of interactions between the primary elements discussed in this chapter. Deterioration in livelihoods, influenced in certain cases by climate change and climate variability, is a human security issue in its own right. But such stress to livelihoods also gives rise to migration, which may be unavoidable and undesirable. Such movements, in turn, imply changes in important cultural expressions and practices, and, in the absence of institutions to manage the settlement and integration of migrants in destination areas, can increase the risk of violent conflict. This conflict can in turn undermine livelihoods, impel migration, and weaken valued cultural expressions and practices. The

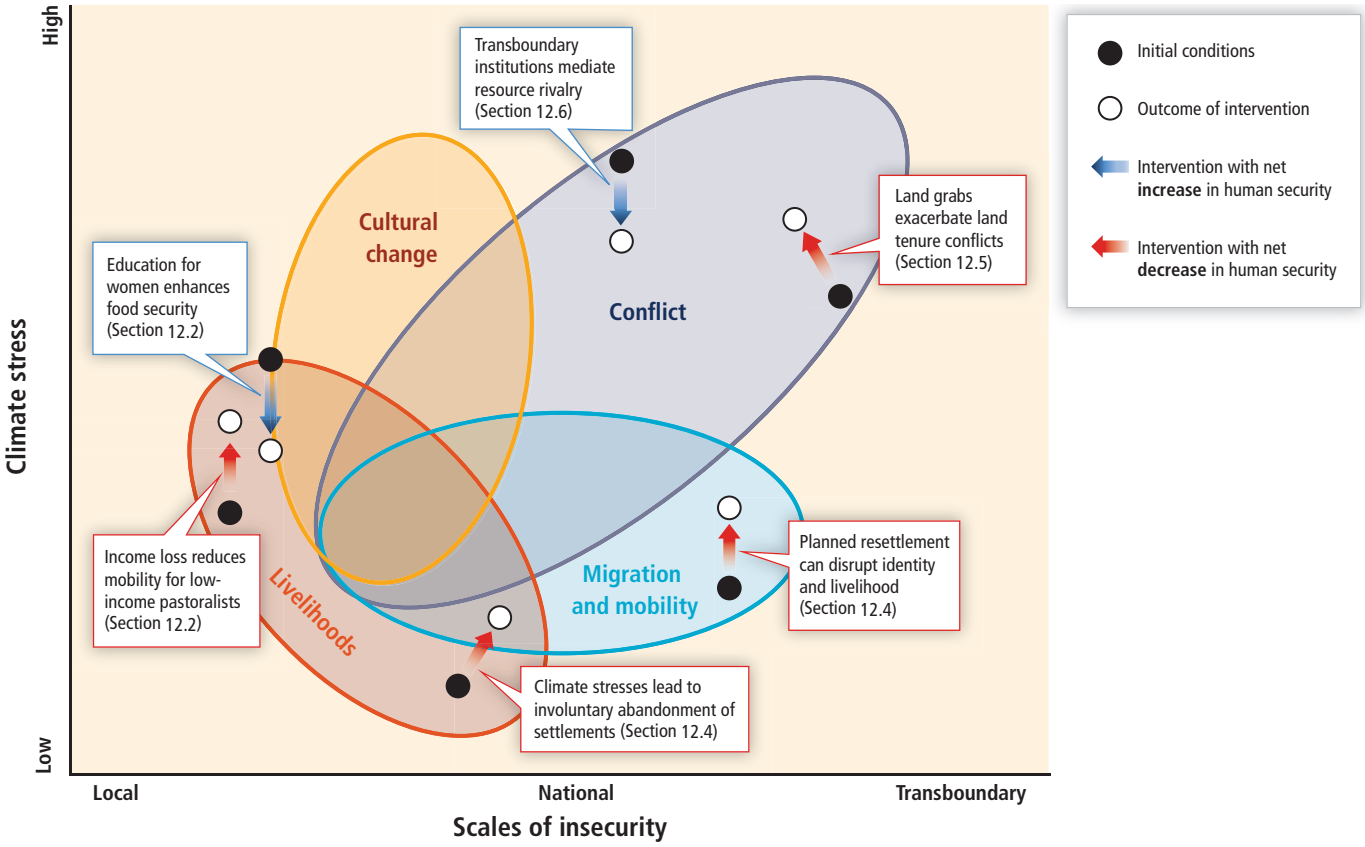
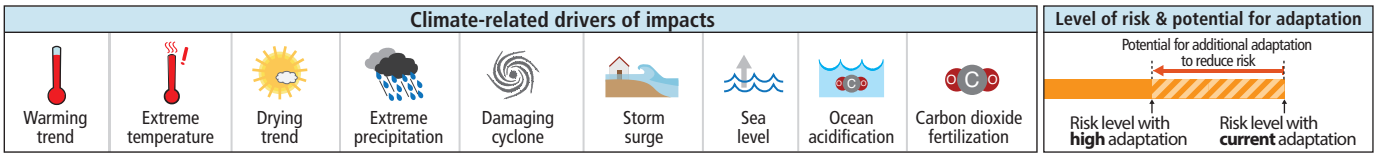


Figure 12-3 | Synthesis of evidence on the impacts of climate change on elements of human security and the interactions between livelihoods, conflict, culture, and migration. Interventions and policies indicated by difference between initial conditions (solid black) and outcome of intervention (white circles). Some interventions (blue arrows) show net increase human security while others (red arrows) lead to net decrease in human security.

Table 12-4 | Examples of important risks from climate change for elements of human security and the potential for risk reduction through mitigation and adaptation. These risks are identified based on this chapter assessment and expert judgments of the authors, with supporting evaluation of evidence and agreement in the relevant chapter sections. Each risk is characterized as *very low*, *low*, *medium*, *high*, or *very high*. Risk levels are presented for the near-term era of committed climate change (here, for 2030–2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer-term era of climate options (here, for 2080–2100), for global mean temperature increase of 2°C and 4°C above pre-industrial levels. For each time frame, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. Relevant climate variables are indicated by symbols. As the assessment considers potential impacts on diverse and incompatible elements and systems, risk levels should not be used to evaluate relative risk between the rows.



Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Displacement associated with extreme events (*high confidence*) [12.4.1]	Adaptation to extreme events is well understood but poorly implemented even under present climate conditions. Displacement and involuntary migration are often temporary. With increasing climate risks, displacement is more likely to involve permanent migration.		Present; Near term (2030 – 2040); Long term 2°C (2080 – 2100) 4°C	Very low; Medium; Very high
Loss of land, cultural and natural heritage disrupting cultural practices embedded in livelihoods and expressed in narratives, world views, identity, community cohesion, and sense of place (*high confidence*) [12.3.2, 12.3.4]	Cultural values and expressions are dynamic and inherently adaptable and hence adaptation is possible to avoid losses of cultural assets and expressions. Nevertheless cultural integrity will be compromised in these circumstances.		Present; Near term (2030 – 2040); Long term 2°C (2080 – 2100) 4°C	Very low; Medium; Very high
Violent conflict arising from deterioration in resource dependent livelihoods such as agriculture and pastoralism (*high confidence*) [12.5.1]	Adaptation options: Buffering rural incomes against climate shocks, e.g., through livelihood diversification, income transfers, and social safety net provision; Early warning mechanisms to promote effective risk reduction; Well-established strategies for managing violent conflict that are effective but require significant resources, investment, and political will.		Present; Near term (2030 – 2040); Long term 2°C (2080 – 2100) 4°C	Very low; Medium; Very high
Geopolitical competition over access to Arctic resources that escalates into dangerous tensions and crises (*high confidence*) [12.6.2]	There are international organizations and elements of international law that regulate competition and access and provide mechanisms for resolving disputes. There are strong transnational networks that are relevant for joint problem solving. Hence adaptation action has significant potential to reduce risks associated with geopolitical rivalry.		Present; Near term (2030 – 2040); Long term 2°C (2080 – 2100) 4°C	Very low; Medium; Very high
New or exacerbated conflict through land acquisition for climate change mitigation and adaptation (*medium confidence*) [12.5.2]	Climate change mitigation (e.g., expansion of biofuel production area) and adaptation action (e.g., set-back of coastal land) can exacerbate conflicts when they are already manifest around land and water availability and scarcity. The extent of insecurity and instability from such mitigation and adaptation activities depends on the displacement of populations and the inclusiveness of the planning processes. Careful planning processes can therefore be used to ameliorate the risk of conflict	*Cumulative climate risks act as incentives for mitigation and adaptation action*	Present; Near term (2030 – 2040); Long term 2°C (2080 – 2100) 4°C	Very low; Medium; Very high

evidence in this chapter shows that some interventions and policies enhance human security, while others inadvertently can exacerbate insecurity (depicted in red and blue arrows in Figure 12-3).

Each dimension of human security examined in this chapter demonstrates the potential for adaptation to minimize risks to human security. Again there is *high agreement* on this finding, reflected in Table 12-4, with multiple lines of evidence from food security, to migration, to conflict resolution. This chapter suggests that often institutions anticipate and react to these risks to human security (Ribot, 2011; Artur and Hilhorst, 2012). These institutional responses can significantly dampen or amplify the way changes in climate change and extreme events give rise to human insecurity. Table 12-4 summarizes a number of example risks to human security, with the final column demonstrating that these risks can be ameliorated through adaptation for many of those examples. In general, higher levels of climate change impacts become less amenable to adaptation.

Adaptation and mitigation strategies and interventions can also affect human insecurity in positive and negative directions. There is evidence that adaptation and mitigation strategies that are imposed on communities are more likely to impact negatively on human security than those that are consistent with their capabilities and values (*limited evidence*, *medium agreement*; Ensor and Berger, 2009; Barnett and O'Neill, 2012;

Marino, 2012; Mercer et al., 2012). Adaptation strategies that seek to reduce exposure to climate change, through the development of large infrastructure or the resettlement of communities against their will, carry risks of disrupted livelihoods, displaced populations, deterioration of valued cultural expressions and practices, and in some cases violent conflict (Table 12-4). Similarly, mitigation policies that entail changes in property regimes that are not consistent with resource ownership and use can impact negatively on human security. There is strong evidence to demonstrate that mitigation activities that align with local interests and institutions can have significant co-benefits for human security, especially through human health (Klein et al., 2005; Ayers and Huq, 2009; Laukkonen et al., 2009; Haines et al., 2009; Moser 2012; West et al., 2013).

In summary, climate change is one of many risks to the vital core of material well-being and culturally specific elements of human security that vary depending on location and circumstance. While there is much uncertainty about the future impacts of climate change on human security, on the basis of current evidence about the observed impacts of climate change on environmental conditions, climate change will be an increasingly important driver of human insecurity in the future (see Figure 12-3). Location and circumstance specific factors include poverty, discrimination, and inadequate provision of public services and public health, and opportunities for education. Investments in institutional responses to facilitate adaptation can dampen many of the potential adverse effects of climate change on human security (see Figure 12-3). Conversely, inappropriate climate policy responses may accelerate and amplify human insecurity including conflict.

At very high levels of projected warming, all aspects of human security discussed in this chapter will be adversely affected (e.g., in high-latitude regions: Box 12-6). At high levels of warming, the rate of changes in environmental conditions in most places will be without any precedent in human history (New et al., 2011). Hence analysis concerning human security in those circumstances of very high impacts (as depicted in Table 12-4) is uncertain. Much of the current literature on human security and climate change is informed by contemporary relationships and observation and hence is limited in analyzing the human security implications of rapid or severe climate change.

References

ACIA, 2005: *Arctic Climate Impact Assessment: Scientific Report.* Arctic Climate Impact Assessment (ACIA), Cambridge University Press, New York, NY, USA, 1042 pp.

Adam, C., 2013: Coping with adversity: the macroeconomic management of natural disasters. *Environmental Science and Policy*, **27(Suppl. 1)**, S99-S111.

Adams, H. and W.N. Adger, 2013: The contribution of ecosystem services to place utility as a determinant of migration decision-making. *Environmental Research Letters*, **8(1)**, 015006, doi:10.1088/1748-9326/8/1/015006.

Adams, V., T.V. Hattum, and D. English, 2009: Chronic disaster syndrome: displacement, disaster capitalism, and the eviction of the poor from New Orleans. *American Ethnologist*, **36(4)**, 615-636.

Adano, W.R., T. Dietz, K. Witsenburg, and F. Zaal, 2012: Climate change, violent conflict and local institutions in Kenya's drylands. *Journal of Peace Research*, **49(1)**, 65-80.

Adelekan, I.O., 2010: Vulnerability of poor urban coastal communities to flooding in Lagos, Nigeria. *Environment and Urbanization*, **22(2)**, 433-450.

Adelman, S., 2010: Rethinking human rights: the impact of climate change on the dominant discourse. In: *Human Rights and Climate Change* [Humphreys, S. (ed.)]. International Council on Human Rights Policy, Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 159-179.

Adger, W.N., 2010: Climate change, human well-being and insecurity. *New Political Economy*, **15(2)**, 275-292.

Adger, W.N. and J. Barnett, 2009: Four reasons for concern about adaptation to climate change. *Environment and Planning A*, **41(12)**, 2800-2805.

Adger, W.N., J. Barnett, F.S. Chapin III, and H. Ellemor, 2011a: This must be the place: under representation of identity and meaning in climate change decision-making. *Global Environmental Politics*, **11(2)**, 1-25.

Adger, W.N., D.R. Nelson, K. Brown, F. Berkes, H. Eakin, C. Folke, K. Galvin, L. Gunderson, M. Goulden, K. O'Brien, J. Ruitenbeek, and E.L. Tompkins, 2011b: Resilience implications of policy responses to climate change. *Wiley Interdisciplinary Reviews: Climate Change* **2(5)**, 757-766.

Adger, W.N., J. Barnett, K. Brown, N. Marshall, and K. O'Brien, 2013: Cultural dimensions of climate change impacts and adaptation. *Nature Climate Change*, **3(2)**, 112-117.

Adler, C.E., D. McEvoy, P. Chhetri, and E. Kruk, 2013: The role of tourism in a changing climate for conservation and development. A problem-oriented study in the Kailash Sacred Landscape, Nepal. *Policy Sciences*, **46(2)**, 161-178.

Adrianto, L. and Y. Matsuda, 2002: Developing economic vulnerability indices of environmental disasters in small island regions. *Environmental Impact Assessment Review*, **22(4)**, 393-414.

Afifi, T. and J. Jäger (eds.), 2010: *Environment, Forced Migration and Social Vulnerability.* Springer-Verlag Berlin Heidelberg, Germany, 271 pp.

Ahmed, S.A., N.S. Diffenbaugh, and T.W. Hertel, 2009: Climate volatility deepens poverty vulnerability in developing countries. *Environmental Research Letters*, **4(3)**, 034004, doi:10.1088/1748-9326/4/3/034004.

Alcántara-Ayala, I., M. López-Mendoza, G. Melgarejo-Palafox, R.C. Borja-Baeza, and R. Acevo-Zarate, 2004: Natural hazards and risk communication strategies among indigenous communities. *Mountain Research and Development*, **24(4)**, 298-302.

Ali, S. and J. Marton-LaFevre (eds.), 2007: *Peace Parks: Conservation and Conflict Resolution.* MIT Press, Cambridge, MA, USA, 406 pp.

Alkire, S., 2003: Concepts of human security. In: *Human Insecurity in a Global World* [Chen, L.C., S. Fukuda-Parr, and E. Seidensticker (eds.)]. Harvard University Press, Cambridge, MA, USA, pp. 15-40.

Anderson, M., L. Holcombe, and D. Williams, 2007: Reducing landslide risk in areas of unplanned housing in the Caribbean – a Government-Community partnership model. *Journal of International Development*, **19(2)**, 205-221.

Angassa, A. and G. Oba, 2008: Herder perceptions on impacts of range enclosures, crop farming, fire ban and bush encroachment on the rangelands of Borana, Southern Ethiopia. *Human Ecology*, **36(2)**, 201-215.

Anik, S.I. and M.A.S.A. Khan, 2012: Climate change adaptation through local knowledge in the north eastern region of Bangladesh. *Mitigation and Adaptation Strategies for Global Change*, **17**, 879-896.

Ardalan, A., K.H. Naieni, M. Mahmoodi, A.M. Zanganeh, A.A. Keshtkar, M.R. Honarvar, and M.J. Kabir, 2010: Flash flood preparedness in Golestan province of Iran: a community intervention trial. *American Journal of Disaster Medicine*, **5(4)**, 197-214.

Arenstam Gibbons, S.J. and R.J. Nicholls, 2006: Island abandonment and sea-level rise: an historical analog from the Chesapeake Bay, USA. *Global Environmental Change*, **16(1)**, 40-47.

Armitage, D., F. Berkes, A. Dale, E. Kocho-Schellenberg, and E. Patton, 2011: Co-management and the co-production of knowledge: learning to adapt in Canada's Arctic. *Global Environmental Change*, **21(3)**, 995-1004.

Arnall, A., 2013: A climate of control: flooding, displacement and planned resettlement in the Lower Zambezi River valley, Mozambique. *The Geographical Journal*, doi:10.1111/geoj.12036.

Artur, L. and D. Hilhorst, 2012: Everyday realities of climate change adaptation in Mozambique. *Global Environmental Change*, **22(2)**, 529-536.

Ashton, A.D., J.P. Jeffrey, P. Donnelly, and R.L. Evans, 2008: A discussion of the potential impacts of climate change on the shorelines of the Northeastern USA. *Mitigation and Adaptation Strategies for Global Change*, **13(7)**, 719-743.

Awuor, C.B., V.A. Orindi, and A.A. Ochieng, 2008: Climate change and coastal cities: the case of Mombasa, Kenya. *Environment and Urbanization*, **20(1)**, 231-242.

Ayers, J.M. and S. Huq, 2009: The value of linking mitigation and adaptation: a case study of Bangladesh. *Environmental Management*, **43(5)**, 753-764.

Badjeck, M., J. Mendo, M. Wolff, and H. Lange, 2009: Climate variability and the Peruvian scallop fishery: the role of formal institutions in resilience building. *Climatic Change*, **94(1-2)**, 211-232.

Badjeck, M., E. Allison, A. Halls, and N. Dulvy, 2010: Impacts of climate variability and change on fishery-based livelihoods. *Marine Policy*, **34(3)**, 375-383.

Ballu, V., M. Bouinc, P. Siméonid, W.C. Crawford, S. Calmante, J. Boréf, T. Kanasg, and B. Pelletiera, 2011: Comparing the role of absolute sea-level rise and vertical tectonic motions in coastal flooding, Torres Islands (Vanuatu). *Proceedings of the National Academy of Sciences of the United States of America*, **108(32)**, 13019-13022.

Barbieri, A.F., E. Domingues, B.L. Queiroz, R.M. Ruiz, J.I. Rigotti, J.A.M. Carvalho, and M.F. Resende, 2010: Climate change and population migration in Brazil's Northeast: scenarios for 2025-2050. *Population and Environment*, **31(5)**, 344-370.

Bardsley, D.K. and G.J. Hugo, 2010: Migration and climate change: examining thresholds of change to guide effective adaptation decision-making. *Population and Environment*, **32(2)**, 238-262.

Barnett, J., 2001: *The Meaning of Environmental Security: Ecological Politics and Policy in the New Security Era.* Zed Books, London, UK and New York, NY, USA, 184 pp.

Barnett, J., 2003: Security and climate change. *Global Environmental Change*, **13(1)**, 7-17.

Barnett, J., 2006: Climate change, insecurity, and injustice. In: *Fairness in Adaptation to Climate Change* [Adger, W.N., J. Paavola, S. Huq, and M. Mace (eds.)]. MIT Press, Cambridge, MA, USA, pp. 115-130.

Barnett, J., 2007: The geopolitics of climate change. *Geography Compass*, **1(6)**, 1361-1375.

Barnett, J., 2009: The prize of peace (is eternal vigilance): a cautionary editorial essay on climate geopolitics. *Climatic Change*, **96(1)**, 1-6.

Barnett, J. and W.N. Adger, 2003: Climate dangers and atoll countries. *Climatic Change*, **61(3)**, 321-337.

Barnett, J. and W.N. Adger, 2007: Climate change, human security and violent conflict. *Political Geography*, **26(6)**, 639-655.

Barnett, J. and J. Campbell, 2010: *Climate Change and Small Island States: Power, Knowledge and the South Pacific.* Earthscan, London, UK and Washington, DC, USA, 218 pp.

Barnett, J. and S. O'Neill, 2010: Maladaptation. *Global Environmental Change*, **20(2)**, 211-213.

Barnett, J. and S.J. O'Neill, 2012: Islands, resettlement and adaptation. *Nature Climate Change*, **2(1)**, 8-10.

Barnett, J. and M. Webber, 2010: Migration as adaptation: opportunities and limits. In: *Climate Change and Displacement: Multidisciplinary Perspectives* [McAdam, J. (ed.)]. Hart Publishing, Oxford, UK, pp. 37-56.

Barnett, J., R.A. Matthew, and K.L. O'Brien, 2010: Global environmental change and human security: an introduction. In: *Global Environmental Change and Human Security* [Matthew, R., B. McDonald, and K. O'Brien (eds.)]. MIT Press, Cambridge, MA, USA, pp. 3-31.

Barrett, C.B., 2010: Measuring food security. *Science*, **327**, 825-828.

Barrett, C.B. 2013: Food or consequences: food security and its implications for global sociopolitical stability. In: *Food Security and Sociopolitical Stability* [Barrett, C.B. (ed.)]. Oxford University Press, Oxford, UK, pp. 1-34.

Barrett, C., K. Smith, and P. Box, 2001: Not necessarily in the same boat: heterogeneous risk assessment among east African pastoralists. *Journal of Development Studies*, **37(5)**, 1-30.

Barrios, S., L. Bertinelli, and E. Strobl, 2006: Climatic change and rural-urban migration: the case of sub-Saharan Africa. *Journal of Urban Economics*, **60(3)**, 357-371.

Bates, D.C., 2002: Environmental refugees? Classifying human migrations caused by environmental change. *Population and Environment*, **23(5)**, 465-477.

Battisti, D.S. and R.L. Naylor, 2009: Historical warnings of future food insecurity with unprecedented seasonal heat. *Science*, **323(5911)**, 240-244.

Bell, D., 2004: Environmental refugees: what rights? Which duties? *Res Publica*, **10(2)**, 135-152.

Bell, D., 2013: Climate change and human rights. *Wiley Interdisciplinary Reviews: Climate Change*, **4**,159-170.

Bellona, M.R., D. Hodson, and J. Hellin, 2011: Assessing the vulnerability of traditional maize seed systems in Mexico to climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **108(33)**, 13432-13437.

Benjaminsen, T.A. and B. Ba, 2009: Farmer-herder conflicts, pastoral marginalization, and corruption: a case study from the inland Niger delta of Mali. *Geographical Journal* **175 (1)**, 71-81.

Benjaminsen, T.A., F. Maganga, and J.M. Abdallah, 2009: The Kilosa killings: political ecology of a farmer-herder conflict in Tanzania. *Development and Change*, **40 (3)**, 423-445.

Benjaminsen, T.A., K. Alinon, H. Buhaug, and J.T. Buseth, 2012: Does climate change drive land-use conflicts in the Sahel? *Journal of Peace Research*, **49(1)**, 97-111.

Berazneva, J. and D.R. Lee, 2013: Explaining the African food riots of 2007-2008: an empirical analysis. *Food Policy*, **39**, 28-39.

Bergholt, D. and P. Lujala, 2012: Climate-related natural disasters, economic growth, and armed civil conflict. *Journal of Peace Research*, **49(1)**, 147-162.

Berhe, A.A., 2007: The contribution of landmines to land degradation. *Land Degradation and Development*, **18(1)**, 1-15.

Berkes, F., 2012: *Sacred Ecology.* 3rd edn., Routledge, Abingdon, UK and New York, NY, USA, 363 pp.

Berkes, F. and D. Armitage, 2010: Co-management institutions, knowledge, and learning: adapting to change in the Arctic. *Études Inuit Studies*, **34(1)**, 109-131.

Berkes, F., T. Hughes, R. Steneck, J.A. Wilson, D. Bellwood, B. Crona, C. Folke, L. Gunderson, H. Leslie, and J. Norberg, 2006: Globalization, roving bandits, and marine resources. *Science*, **311(5767)**, 1557-1558.

Berkman, P.A., 2010: *Environmental Security in the Arctic Ocean.* Routledge, Abingdon, UK and New York, NY, USA, 160 pp.

Bernauer, T. and T. Siegfried, 2012: Climate change and international water conflict in Central Asia. *Journal of Peace Research*, **49(1)**, 227-239.

Bernauer, T., T. Böhmelt, and V. Koubi, 2012: Environmental changes and violent conflict. *Environmental Research Letters*, **7(1)**, 015601, doi:10.1088/1748-9326/7/1/015601.

Berrang-Ford, L., J.D. Ford, and J. Paterson, 2011: Are we adapting to climate change? *Global Environmental Change*, **21**, 25-33.

Betancourt, T.S., M.K.S. Fawzi, C. Bruderlein, C. Desmond, and J.Y. Kim, 2010: Children affected by HIV/AIDS: SAFE, a model for promoting their security, health, and development. *Psychology, Health and Medicine*, **15(3)**, 243-265.

Bettini, G., 2013: Climate barbarians at the gate? A critique of apocalyptic narratives on 'climate refugees'. *Geoforum*, **45**, 63-72.

Beymer-Farris, B.A. and T.J. Bassett, 2012: The REDD menace: resurgent protectionism in Tanzania's mangrove forests. *Global Environmental Change*, **22(2)**, 332-341.

Beymer-Farris, B.A., and T.J. Bassett, 2013: Environmental narratives and politics in Tanzania's Rufiji Delta: a reply to Burgess et al. *Global Environmental Change*, **23(5)**, 1355-1358, doi.org/10.1016/j.gloenvcha.2013.06.007.

Biermann, F. and I. Boas, 2008: Protecting climate refugees: the case for a global protocol. *Environment: Science and Policy for Sustainable Development*, **50(6)**, 8-17.

Biermann, F. and I. Boas, 2012: Climate change and human migration: towards a global governance system to protect climate refugees. In: *Climate Change, Human Security and Violent Conflict: Challenges for Societal Stability* [Scheffran, J., M. Brzoska, H.G. Brauch, P.M. Link, and J. Schilling (eds.)]. Springer-Verlag Berlin Heidelberg, Germany, pp. 291-300.

Black, D.R. and L.A. Swatuk, 2009: Human security in North America: a Canadian perspective. In: *Facing Global Environmental Change: Environmental, Human, Energy, Food, Health and Water Security Concepts* [Brauch, H.G., Ú. Oswald Spring, J. Grin, C. Mesjasz, P. Kameri-Mbote, N.C. Behera, B. Chourou, and H. Krummenacher (eds.)]. Springer-Verlag Berlin Heidelberg, Germany, pp. 1087-1096.

Black, R., S.R.G. Bennett, S.M. Thomas, and J.R. Beddington, 2011a: Climate change: migration as adaptation. *Nature*, **478(7370)**, 447-449.

Black, R., W.N. Adger, N.W. Arnell, S. Dercon, A. Geddes, and D. Thomas, 2011b: The effect of environmental change on human migration. *Global Environmental Change*, **21(Suppl. 1)**, S3-S11.

Black, R., D. Kniveton, and K. Schmidt-Verkerk, 2011c: Migration and climate change: towards an integrated assessment of sensitivity. *Environment and Planning A*, **43(2)**, 431-450.

Black, R., N.W. Arnell, W.N. Adger, D. Thomas, and A. Geddes, 2013: Migration, immobility and displacement outcomes of extreme events. *Environmental Science and Policy*, **27(Suppl. 1)**, S32-S43.

Blattman, C. and E. Miguel, 2010: Civil war. *Journal of Economic Literature*, **48(1)**, 3-57.

Bodansky, D., 2010: Climate change and human rights: unpacking the issues. *Georgia Journal of International and Comparative Law*, **38**, 511-524.

Bogale, A. and B. Korf, 2007: To share or not to share? (Non-)violence, scarcity and resource access in Somali Region, Ethiopia. *Journal of Development Studies*, **43(4)**, 743-765.

Bohle, H.-G., 2009: Sustainable livelihood security. Evolution and application. In: *Facing Global Environmental Change: Environmental, Human, Energy, Food, Health and Water Security* [Brauch, H.G., Ú. Oswald Spring, J. Grin, C. Mesjasz, P. Kameri-Mbote, N.C. Behera, B. Chourou, and H. Krummenacher (eds.)]. Springer-Verlag, Berlin, Heidelberg, Germany, pp. 521-528.

Bohra-Mishra, P. and D.S. Massey, 2011: Environmental degradation and out-migration: evidence from Nepal. In: *Migration and Climate Change* [Piguet, É., A. Pécoud, and P.d. Guchteneire (eds.)]. United Nations Educational, Scientific and Cultural Organization (UNESCO), Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 74-101.

Borgerson, S.G., 2008: Arctic meltdown: the economic and security implications of global warming. *Foreign Affairs*, **87(2)**, 63-77.

Borras Jr, S.M., P. McMichael, and I. Scoones, 2010: The politics of biofuels, land and agrarian change: editors' introduction. *Journal of Peasant Studies*, **37(4)**, 575-592.

Boyle, M., Y. Racine, K. Georgiades, D. Snelling, S. Hong, W. Omariba, P. Hurley, and P. Rao-Melacini, 2006: The influence of economic development level, household wealth and maternal education on child health in the developing world. *Social Science and Medicine*, **63(8)**, 2242-2254.

Brauch, H.G., 2009: Securitizing global environmental change. In: *Facing Global Environmental Change: Environmental, Human, Energy, Food, Health and Water Security Concepts* [Brauch, H.G., Ú. Oswald Spring, J. Grin, C. Mesjasz, P. Kameri-Mbote, N.C. Behera, B. Chourou, and H. Krummenacher (eds.)]. Springer-Verlag, Berlin, Heidelberg, Germany, pp. 65-102.

Brauch, H.G., Ú. Oswald Spring, C. Mesjasz, J. Grin, P. Dunay, N.C. Behera, B. Chourou, P. Kameri-Mbote, and P.H. Liotta (eds.), 2008: *Globalization and Environmental Challenges: Reconceptualizing Security in the 21st Century.* Hexagon Series on Human and Environmental Security and Peace, Vol. 3, Springer-Verlag, Berlin, Heidelberg, Germany, 1176 pp.

Brauch, H.G., Ú. Oswald Spring, J. Grin, C. Mesjasz, P. Kameri-Mbote, N.C. Behera, B. Chourou, and H. Krummenacher (eds.), 2009: *Facing Global Environmental Change: Environmental, Human, Energy, Food, Health and Water Security Concepts.* Springer-Verlag, Berlin, Heidelberg, Germany, 1546 pp.

Brauch, H.G., Ú. Oswald Spring, C. Mesjasz, J. Grin, P. Kameri-Mbote, B. Chourou, P. Dunay, and J. Birkmann (eds.), 2011: *Coping with Global Environmental Change, Disasters and Security: Threats, Challenges, Vulnerabilities and Risks.* Springer-Verlag, Berlin, Heidelberg, Germany, 1815 pp.

Brklacich, M., M. Chazan, and H.G. Bohle, 2010: Human security, vulnerability, and global environmental change. In: *Global Environmental Change and Human Security* [Matthew, R., J. Barnett, B. McDonald, and K. O'Brien (eds.)]. MIT Press, Cambridge, MA, USA, pp. 35-76.

Brochmann, M. and P.R. Hensel, 2009: Peaceful management of international river claims. *International Negotiation*, **14(2)**, 393-418.

Bronen, R., 2010: Forced migration of Alaskan indigenous communities due to climate change. In: *Environment, Forced Migration and Social Vulnerability* [Afifi, T. and J. Jäger (eds.)]. Springer-Verlag Berlin Heidelberg, Germany, pp. 87-98.

Bronen, R., 2011: Climate-induced community relocations: creating an adaptive governance framework based in human rights doctrine. *New York University Review of Law and Social Change*, **35**, 357-407.

Bronen, R. and F.S. Chapin, 2013: Adaptive governance and institutional strategies for climate-induced community relocations in Alaska. *Proceedings of the National Academy of Sciences of the United States of America*, **100(23)**, 9320-9325.

Brook, T., 2010: *The Troubled Empire: China in the Yuan and Ming Dynasties.* Belknap Press, Cambridge, MA, USA, 329 pp.

Brosnan, I.G., T.M. Leschine, and E.L. Miles, 2011: Cooperation or conflict in a changing Arctic? *Ocean Development and International Law*, **42(1-2)**, 173-210.

Brown, H.C.P., 2009: Climate change and Ontario forests: prospects for building institutional adaptive capacity. *Mitigation and Adaptation Strategies for Global Change*, **14(6)**, 513-536.

Brown, H.C.P., B. Smit, D.J. Sonwa, O.A. Somorin, and J. Nkem, 2011: Institutional perceptions of opportunities and challenges of REDD in the Congo Basin. *Journal of Environment and Development*, **20(4)**, 381-404.

Brown, I.A., 2010: Assessing eco-scarcity as a cause of the outbreak of conflict in Darfur: a remote sensing approach. *International Journal of Remote Sensing*, **31(10)**, 2513-2520.

Brown, S. and F. Bean, 2005: International migration. In: *Handbook of Population* [Poston, D.L. and M. Micklin (eds.)]. Kluwer, Dordrecht, Netherlands, pp. 347-382.

Brückner, M. and A. Ciccone, 2010: International commodity prices, growth and the outbreak of civil war in sub-Saharan Africa. *Economic Journal*, **120(544)**, 519-534.

Brückner, M. and A. Ciccone, 2011: Rain and the democratic window of opportunity. *Econometrica*, **79(3)**, 923-947.

Brzoska, M., 2012: Climate change as a driver of security policy. In: *Climate Change, Human Security and Violent Conflict: Challenges for Societal Stability* [Scheffran, J., M. Brzoska, H.G. Brauch, P.M. Link, and J. Schilling (eds.)]. Springer-Verlag, Berlin Heidelberg, Germany, pp. 165-184.

Buckley, B.M., K.J. Anchukaitis, D. Penny, R. Fletcher, E.R. Cook, M. Sano, L.C. Nam, A. Wichienkeeo, T.T. Minh, and T.M. Hong, 2010: Climate as a contributing factor in the demise of Angkor, Cambodia. *Proceedings of the National Academy of Sciences of the United States of America*, **107(15)**, 6748-6752.

Buhaug, H., 2010: Climate not to blame for African civil wars. *Proceedings of the National Academy of Sciences of the United States of America*, **107(38)**, 16477-16482.

Buhaug, H. and O.M. Theisen, 2012: On environmental change and armed conflict. In: *Climate Change, Human Security and Violent Conflict: Challenges for Societal Stability* [Scheffran, J., M. Brzoska, H.G. Brauch, P.M. Link, and J. Schilling (eds.)]. Springer-Verlag Berlin Heidelberg, Germany, pp. 43-55.

Buhaug, H. and H. Urdal, 2013: An urbanization bomb? Population growth and social disorder in cities. *Global Environmental Change*, **23(1)**, 1-10.

Buikstra, E., H. Ross, C.A. King, P.G. Baker, D. Hegney, K. McLachlan, and C. Rogers-Clark, 2010: The components of resilience – perceptions of an Australian rural community. *Journal of Community Psychology*, **38(8)**, 975-991.

Bumpus, A.G. and D.M. Liverman, 2008: Accumulation by decarbonization and the governance of carbon offsets. *Economic Geography*, **84(2)**, 127-155.

Burgess, N.D., S. Mwakalila, P. Munishi, M. Pfeifer, S. Willcock, D. Shirima, S. Hamidu, G.B. Bulenga, J. Rubens, H. Machano, and R. Marchant, 2013: REDD herrings or REDD menace: response to Beymer-Farris and Bassett. *Global Environmental Change*, **23(5)**, 1349-1354, doi.org/10.1016/j.gloenvcha.2013.05.013.

Burke, M.B., E. Miguel, S. Satyanath, J.A. Dykema, and D.B. Lobell, 2009: Warming increases the risk of civil war in Africa. *Proceedings of the National Academy of Sciences of the United States of America*, **106(49)**, 20670-20674.

Burningham, K., J. Fielding, and D. Thrush, 2008: 'It'll never happen to me': understanding public awareness of local flood risk. *Disasters*, **32(2)**, 216-238.

Burns, R., P. Robinson, and P. Smith, 2010: From hypothetical scenario to tragic reality: a salutary lesson in risk communication and the Victorian 2009 bushfires. *Australian and New Zealand Journal of Public Health*, **34(1)**, 24-31.

Busby, J.W., 2008: Who cares about the weather? Climate change and US national security. *Security Studies*, **17(3)**, 468-504.

Busby, J.W., T.G. Smith, K.L. White, and S.M. Strange, 2013: Climate change and insecurity. Mapping vulnerability in Africa. *International Security* **37(4)**, 132-172.

Butler, C.K. and S. Gates, 2012: African range wars: climate, conflict, and property rights. *Journal of Peace Research*, **49(1)**, 23-34.

Butzer, K.W., 2012: Collapse, environment, and society. *Proceedings of the National Academy of Sciences of the United States of America*, **109(10)**, 3632-3639.

Byravan, S. and S.C. Rajan, 2006: Providing new homes for climate change exiles. *Climate Policy*, **6(2)**, 247-252.

Cameron, E.S., 2012: Securing indigenous politics: a critique of the vulnerability and adaptation approach to the human dimensions of climate change in the Canadian Arctic. *Global Environmental Change*, **22(1)**, 103-114.

Caney, S., 2010: Climate change, human rights and moral thresholds. In: *Human Rights and Climate Change* [Humphreys, S. (ed.)]. International Council on Human Rights Policy, Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 69-90.

Carlarne, C. and M. Depledge, 2007: Sick of the weather: climate change, human health and international law. *Environmental Law Review* **9**, 231-240.

Carmack, E., F. McLaughlin, G. Whiteman, and T. Homer-Dixon, 2012: Detecting and coping with disruptive shocks in Arctic marine systems: a resilience approach to place and people. *Ambio*, **41**, 56-65.

Carter, M., P. Little, T. Mogues, and W. Negatu, 2007: Poverty traps and natural disasters in Ethiopia and Honduras. *World Development*, **35(5)**, 835-856.

Catto, N.R. and K. Parewick, 2008: Hazard and vulnerability assessment and adaptive planning: mutual and multilateral community-researcher communication, Arctic Canada. *Geological Society, London, Special Publications*, **305(1)**, 123-140.

Chase, M.J. and C.R. Griffin, 2011: Elephants of south-east Angola in war and peace: their decline, re-colonization and recent status. *African Journal of Ecology*, **49(3)**, 353-361.

Chatterjee, M., 2010: Slum dwellers response to flooding events in the megacities of India. *Mitigation and Adaptation Strategies for Global Change*, **15(4)**, 337-353.

Chourou, B., 2009: Human security in the Arab world: a perspective from the Maghreb. In: *Facing Global Environmental Change: Environmental, Human, Energy, Food, Health and Water Security Concepts* [Brauch, H.G., Ú. Oswald Spring, J. Grin, C. Mesjasz, P. Kameri-Mbote, N.C. Behera, B. Chourou, and H. Krummenacher (eds.)]. Springer-Verlag, Berlin, Heidelberg, Germany, pp. 1021-1035.

Cohen, M.J. and J.L. Garrett, 2010: The food price crisis and urban food (in)security. *Environment and Urbanization* **22**, 467-482.

Commission on Human Security, 2003: *Human Security Now: Protecting and Empowering People.* Commission on Human Security (CHS), Human Security Unit, United Nations Office for the Coordination of Humanitarian Affairs (OCHA), New York, NY, USA, 159 pp.

Conca, K., 2005: *Governing Water: Contentious Transnational Politics and Global Institution Building.* MIT Press, Cambridge, MA, USA, 466 pp.

Conca, K. and G. Dabelko (eds.), 2002: *Environmental Peacemaking.* Johns Hopkins University Press, Baltimore, MD, USA, 244 pp.

Conca, K. and J. Wallace, 2009: Environment and peacebuilding in war-torn societies: lessons from the UN Environment Programme's experience with postconflict assessment. *Global Governance*, **15(4)**, 185-105.

Conca, K., F. Wu, and C. Mei, 2006: Global regime formation or complex institution building? The principled content of international river agreements. *International Studies Quarterly*, **50(2)**, 263-285.

Corner, A. and N. Pidgeon, 2010: Geoengineering the climate: the social and ethical implications. *Environment: Science and Policy for Sustainable Development*, **52(1)**, 24-37.

Costello, A., M. Abbas, A. Allen, S. Ball, S. Bell, R. Bellamy, S. Friel, N. Groce, A. Johnson, M. Kett, M. Lee, C. Levy, M. Maslin, D. McCoy, B. McGuire, H. Montgomery, D. Napier, C. Pagel, J. Patel, J.A.P.d. Oliveira, N. Redclift, H. Rees, D. Rogger, J. Scott, J. Stephenson, J. Twigg, J. Wolff, and C. Patterson, 2009: Managing the health effects of climate change. *The Lancet*, **373(9676)**, 1693-1733.

Coulthard, S., 2008: Adapting to environmental change in artisanal fisheries – insights from a south Indian lagoon. *Global Environmental Change*, **18(3)**, 479-489.

Cournil, C., 2011: The protection of environmental refugees in international law. In: *Climate Change and Migration* [Piguet, E., A. Pecoud, and P. de Guchteneire (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 359-387.

Crate, S.A., 2008: Gone the bull of winter? Grappling with the cultural implications of and anthropology's role(s) in global climate change. *Current Anthropology*, **49(4)**, 569-595.

Crate, S.A., 2011: Climate and culture: anthropology in the era of contemporary climate change. *Annual Review of Anthropology*, **(40)**, 175-194.

Crate, S.A. and M. Nuttall (eds.), 2009: *Anthropology and Climate Change: From Encounters to Actions.* Left Coast Press, Walnut Creek, CA, USA, 416 pp.

Cunsolo-Willox, A., S.L. Harper, J.D. Ford, K. Landman, K. Houle, V.L. Edge, and the Rigolet Inuit Community Government, 2012: "From this place and of this place:" climate change, sense of place, and health in Nunatsiavut, Canada, *Social Science & Medicine*, **75(3)**, 538-547.

Cunsolo-Willox, A., S.L. Harper, V.L. Edge, K. Landman, K. Houle, J.D. Ford, and the Rigolet Inuit Community Government, 2013: The land enriches the soul: on climatic and environmental change, affect, and emotional health and well-being in Rigolet, Nunatsiavut, Canada. *Emotion, Space and Society*, **6**, 14-24.

Curtis, K. and A. Schneider, 2011: Understanding the demographic implications of climate change: estimates of localized population predictions under future scenarios of sea-level rise. *Population and Environment*, **33(1)**, 28-54.

Dabelko, G.D., 2009: Planning for climate change: the security community's precautionary principle. *Climatic Change*, **96(1)**, 13-21.

Dalby, S., 2009: *Security and Environmental Change.* Polity Press, Cambridge, UK, and Malden, MA, USA, 197 pp.

Dalby, S., 2013: Climate change, *The RUSI Journal*, **158(3)**, 34-43.

Dannevig H., T. Rauken, and G. Hovelsrud, 2012: Implementing adaptation to climate change at the local level. *Local Environment: The International Journal of Justice and Sustainability*, **17 (6-7)**, 597-611.

Dauvergne, P. and K.J. Neville, 2010: Forests, food, and fuel in the tropics: the uneven social and ecological consequences of the emerging political economy of biofuels. *Journal of Peasant Studies*, **37(4)**, 631-660.

Davidson, D.J., T. Williamson, and J.R. Parkins, 2003: Understanding climate change risk and vulnerability in northern forest-based communities. *Canadian Journal of Forest Research*, **33(11)**, 2252-2261.

de Moel, H., J.C.J.H. Aerts, and E. Koomen, 2011: Development of flood exposure in the Netherlands during the 20th and 21st century. *Global Environmental Change*, **21(2)**, 620-627.

de Sherbinin, A., L.K. VanWey, K. McSweeney, R. Aggarwal, A. Barbieri, S. Henry, L.M. Hunter, W. Twine, and R. Walker, 2008: Rural household demographics, livelihoods and the environment. *Global Environmental Change*, **18(1)**, 38-53.

de Sherbinin, A., M. Castro, F. Gemenne, M. Cernea, S. Adamo, P. Fearnside, G. Krieger, S. Lahmani, A. Oliver-Smith, and A. Pankhurst, 2011: Preparing for resettlement associated with climate change. *Science*, **334(6055)**, 456-457.

de Sherbinin, A., M. Levy, S. Adamo, K. MacManus, G. Yetman, V. Mara, L. Razafindrazay, B. Goodrich, T. Srebotnjak, C. Aichele, and L. Pistolesi, 2012: Migration and risk: net migration in marginal ecosystems and hazardous areas. *Environmental Research Letters*, **7(4)**, 045602, doi:10.1088/1748-9326/7/4/045602.

De Stefano, L., P. Edwards, L. De Silva, and A.T. Wolf, 2010: Tracking cooperation and conflict in international basins: historic and recent trends. *Water Policy*, **12(6)**, 871-884.

De Stefano, L., J. Duncan, S. Dinar, K. Stahl, K.M. Strzepek, and A.T. Wolf, 2012: Climate change and the institutional resilience of international river basins. *Journal of Peace Research*, **49(1)**, 193-209.

de Waal, A., 1993: War and famine in Africa. *IDS Bulletin*, **24(4)**, 33-40.

De Weijer, F., 2007: Afghanistan's kuchi pastoralists: change and adaptation. *Nomadic Peoples*, **11(1)**, 9-37.

Deligiannis, T., 2012: The evolution of environment-conflict research: toward a livelihood framework. *Global Environmental Politics*, **12(1)**, 78-100.

Dellapena, J.W. and J. Gupta (eds.), 2009: *The Evolution of the Law and Politics of Water.* Springer Science, Dordrecht, Netherlands, 413 pp.

DeMenocal, P.B., 2001: Cultural responses to climate change during the late Holocene. *Science*, **292(5517)**, 667-673.

Deng, L.B., 2008: Are non-poor households always less vulnerable? The case of households exposed to protracted civil war in Southern Sudan. *Disasters*, **32(3)**, 377-398.

Deng, L.B., 2010a: Livelihood diversification and civil war: Dinka communities in Sudan's civil war. *Journal of Eastern African Studies*, **4(3)**, 381-399.

Deng, L.B., 2010b: Social capital and civil war: the Dinka communities in Sudan's civil war. *African Affairs*, **109(435)**, 231-250.

Dercon, S. (ed.), 2004: *Insurance against Poverty.* Oxford University Press, Oxford, UK and New York, NY, USA, 465 pp.

Deressa, T.T. and R.M. Hassan, 2009: Economic impact of climate change on crop production in Ethiopia: evidence from cross-section measures. *Journal of African Economies*, **18(4)**, 529-554.

Dersken, C., S.L. Smith, M. Sharp, L. Brown, S. Howell, L. Copeland, D.R. Mueller, Y. Gauthier, C.G. Fletcher, A. Tivy, M. Bernier, J. Bourgeois, R. Brown, C.R. Burn, C. Duguay, P. Kushner, A. Langlois, A.G. Lewkowicz, A. Royer, and A. Walker, 2012: Variability and change in the Canadian cyrosphere. *Climatic Change*, **115 (1)**, 59-88.

Deshingkar, P., 2012: Environmental risk, resilience and migration: implications for natural resource management and agriculture. *Environmental Research Letters* **7(1)**, 015603, doi:10.1088/1748-9326/7/1/015603.

Desta, S. and D.L. Coppock, 2004: Pastoralism under pressure: tracking system change in southern Ethiopia. *Human Ecology*, **32(4)**, 465-486.

Detraz, N., 2009: Environmental security and gender: necessary shifts in an evolving debate. *Security Studies*, **18(2)**, 345-369.

Dinar, S., A. Dinar, and P. Kurukulasuriya, 2011: Scarcity and cooperation along international rivers: an empirical assessment of bilateral treaties. *International Studies Quarterly*, **55(3)**, 809-833.

Dixon, J., 2009: What causes civil wars? Integrating quantitative research findings. *International Studies Review*, **11(4)**, 707-735.

Docherty, B. and T. Giannini, 2009: Confronting a rising tide: a proposal for a convention on climate change refugees. *Harvard Environmental Law Review*, **33(2)**, 349-403.

Doherty, T.J. and S. Clayton, 2011: The psychological impacts of global climate change. *American Psychologist*, **66(4)**, 265-276.

Downing, T.E., 2002: Linking sustainable livelihoods and global climate change in vulnerable food systems. *Die Erde*, **133(4)**, 363-378.

Drimie, S. and S. Gillespie, 2010: Adaptation to climate change in Southern Africa: factoring in AIDS. *Environmental Science and Policy*, **13(8)**, 778-784.

Duarte, C.M., T.M. Lenton, P. Wadhams, and P. Wassmann, 2012: Abrupt climate change in the Arctic. *Nature Climate Change*, **2(2)**, 60-62.

Duffy, R., 2002: Peace parks: the paradox of globalisation? *Geopolitics*, **6(2)**, 1-26, doi:10.1080/14650040108407715.

Dumaru, P., 2010: Community-based adaptation: enhancing community adaptive capacity in Druadrua Island, Fiji. *Wiley Interdisciplinary Reviews: Climate Change*, **1(5)**, 751-763.

Dun, O., 2011: Migration and displacement triggered by floods in the Mekong Delta. *International Migration*, **49(Suppl. 1)**, e200-e223.

Eakin, H., K. Benessaiah, J. Barrera, G. Cruz-Bello, and H. Morales, 2012: Livelihoods and landscapes at the threshold of change: disaster and resilience in a Chiapas coffee community. *Regional Environmental Change*, **12(3)**, 475-488.

Ebinger, C.K. and E. Zambetakis, 2009: The geopolitics of Arctic melt. *International Affairs*, **85**, 1215-1232.

Eboli, F., R. Parrado, and R. Roson, 2010: Climate-change feedback on economic growth: explorations with a dynamic general equilibrium model. *Environment and Development Economics*, **15(5)**, 515-533.

Eira, I.M.G., C. Jaedicke, O.H. Magga, N.G. Maynard, D. Vikhamar-Schuler, and S.D. Mathiesen, 2013: Traditional Sámi snow terminology and physical snow classification – two ways of knowing. *Cold Regions Science and Technology*, **85**, 117-130.

Ellemor, H., 2005: Reconsidering emergency management and indigenous communities in Australia. *Global Environmental Change Part B: Environmental Hazards*, **6(1)**, 1-7.

Elliott, J.R. and J. Pais, 2006: Race, class, and Hurricane Katrina: social differences in human responses to disaster. *Social Science Research*, **35(2)**, 295-321.

Ellis, F., 2000: *Rural Livelihoods and Diversity in Developing Countries.* Oxford University Press, Oxford, UK and New York, NY, USA, 273 pp.

Emperaire, L. and N. Peroni, 2007: Traditional management of agrobiodiversity in Brazil: a case study of manioc. *Human Ecology*, **35(6)**, 761-768.

Ensor, J. and R. Berger, 2009: Community-based adaptation and culture in theory and practice. In: *Adapting to Climate Change: Thresholds, Values and Governance* [Adger, W.N., I. Lorenzoni, and K. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 227-239.

Eriksen, S. and J. Lind, 2009: Adaptation as a political process: adjusting to drought and conflict in Kenya's drylands. *Environmental Management*, **43(5)**, 817-835.

Eriksen, S., P. Aldunce, C.S. Bahinipati, R.D.A. Martins, J.I. Molefe, C. Nhemachena, K. O'Brien, F. Olorunfemi, J. Park, and L. Sygna, 2011:When not every response to climate change is a good one: identifying principles for sustainable adaptation. *Climate and Development*, **3**, 7-20.

Fairhead, J., M. Leach, and I. Scoones, 2012: Green grabbing: a new appropriation of nature? *Journal of Peasant Studies*, **39(2)**, 237-261.

Falk, W.W., M.O. Hunt, and L.L. Hunt, 2006: Hurricane Katrina and New Orleanians' sense of place. *Du Bois Review*, **3(1)**, 115-128.

Farbotko, C., 2010: Wishful sinking: disappearing islands, climate refugees and cosmopolitan experimentation. *Asia Pacific Viewpoint*, **51(1)**, 47-60.

Farbotko, C. and H. Lazrus, 2012: The first climate refugees? Contesting global narratives of climate change in Tuvalu. *Global Environmental Change*, **22(2)**, 382-390.

Fazey, I., M. Kesby, A. Evely, I. Latham, D. Wagatora, J. Hagasua, M.S. Reed, and M. Christie, 2010: A three-tiered approach to participatory vulnerability assessment in the Solomon Islands. *Global Environmental Change*, **20(4)**, 713-728.

Feitelson, E., A. Tamimi, and G. Rosenthal, 2012: Climate change and security in the Israeli-Palestinian context. *Journal of Peace Research*, **49(1)**, 241-257.

Feng, S., A.B. Krueger, and M. Oppenheimer, 2010: Linkages among climate change, crop yields and Mexico-US cross-border migration. *Proceedings of the National Academy of Sciences of the United States of America*, **107(32)**, 14257-14262.

Fernández-Giménez, M.E., B. Batkhishig, and B. Batbuyan, 2012: Cross-boundary and cross-level dynamics increase vulnerability to severe winter disasters (dzud) in Mongolia. *Global Environmental Change*, **22(4)**, 836-851.

Fernando, N., K. Warner, and J. Birkmann, 2010: Migration and natural hazards: is relocation a secondary disaster or an opportunity for vulnerability reduction? In: *Environment, Forced Migration and Social Vulnerability* [Afifi, T. and J. Jäger (eds.)]. Springer-Verlag, Berlin, Heidelberg, Germany, pp. 145-156.

Findley, S.E., 1994: Does drought increase migration? A study of migration from rural Mali during the 1983-1985 drought. *International Migration Review*, **28(3)**, 539-553.

Finucane, M.L., 2009: Why science alone won't solve the climate crisis: managing climate risks in the Pacific. *AsiaPacific Issues*, **89**, 1-8.

Fisher, P.B., 2011: Climate change and human security in Tuvalu. *Global Change, Peace & Security*, **23(3)**, 293-313.

Fjelde, H. and N. von Uexkull, 2012: Climate triggers: rainfall anomalies, vulnerability and communal conflict in Sub-Saharan Africa. *Political Geography*, **31(7)**, 444-453.

Fleming, J.R., 2010: *Fixing the Sky: The Checkered History of Weather and Climate Control.* Columbia University Press, New York, NY, USA, 325 pp.

Flint, C.G., E.S. Robinson, J. Kellogg, G. Ferguson, L. BouFajreldin, M. Dolan, I. Raskin, and M.A. Lila, 2011: Promoting wellness in Alaskan villages: integrating traditional knowledge and science of wild berries. *Ecohealth*, **8(2)**, 199-209, doi:10.1007/s10393-011-0707-9.

Floyd, R., 2008: The environmental security debate and its significance for climate change. *The International Spectator*, **43(3)**, 51-65.

Forbes, B.C., 2007: Equity, vulnerability and resilience in social-ecological systems: a contemporary example from the Russian Arctic. In: *Equity and the Environment* [Freudenburg, W.R. and R. Wilkinson (eds.)]. Elsevier, Oxford, UK, pp. 203-236.

Ford, J.D. and C. Goldhar, 2012: Climate change vulnerability and adaptation in resource dependent communities: a case study from West Greenland. *Climate Research*, **54**, 181-196.

Ford, J.D., B. Smit, J. Wandel, and J. MacDonald, 2006: Vulnerability to climate change in Igloolik, Nunavut: what we can learn from the past and present. *Polar Record*, **42(2)**, 127-138.

Ford, J.D., T. Pearce, B. Smit, J. Wandel, M. Allurut, K. Shappa, H. Ittusujurat, and K. Qrunnut, 2007: Reducing vulnerability to climate change in the Arctic: the case of Nunavut, Canada. *Arctic*, **60(2)**, 150-166.

Ford, J.D., T. Pearce, J. Gilligan, B. Smit, and J. Oakes, 2008: Climate change and hazards associated with ice use in northern Canada. *Arctic, Antarctic, and Alpine Research*, **40(4)**, 647-659.

Ford, J.D., W. Gough, G. Laidler, J. MacDonald, C. Irngaut, and K. Qrunnut, 2009: Sea ice, climate change, and community vulnerability in northern Foxe Basin, Canada. *Climate Research*, **38(2)**, 137-154.

Ford, J.D., T. Pearce, F. Duerden, C. Furgal, and B. Smit, 2010: Climate change policy responses for Canada's Inuit population: the importance of and opportunities for adaptation. *Global Environmental Change*, **20(1)**, 177-191.

Foresight, 2011: *Migration and Global Environmental Change: Future Challenges and Opportunities.* Final Project Report, UK Government Office for Science, London, UK, 236 pp.

Fox, S. and J. Beall, 2012: Mitigating conflict and violence in African cities. *Environment and Planning C: Government and Policy*, **30(6)**, 968-981.

Frazier, T.G., N. Wood, and B. Yarnal, 2010: Stakeholder perspectives on land-use strategies for adapting to climate-change-enhanced coastal hazards: Sarasota, Florida. *Applied Geography*, **30(4)**, 506-517.

Frey, W.H. and A. Singer, 2006: *Katrina and Rita Impacts on Gulf Coast Populations: First Census Findings.* Brookings Institution, Metropolitan Policy Program, Washington DC.

Furgal, C. and J. Seguin, 2006: Climate change, health and vulnerability in Canadian northern Aboriginal communities. *Environmental Health Perspectives*, **114(2)**, 1964-1970.

Fussell, E., N. Sastry, and M. Van Landingham, 2010: Race, socioeconomic status, and return migration to New Orleans after Hurricane Katrina. *Population and Environment*, **31(1-3)**, 20-42.

Galvin, K., 2009: Transitions: pastoralists living with change. *Annual Review of Anthropology*, **38**, 185-198.

Gartzke, E., 2012: Could climate change precipitate peace? *Journal of Peace Research*, **49(1)**, 177-192.

Gasper, D., 2005: Securing humanity: situating human security as concept and discourse. *Journal of Human Development*, **6(2)**, 221-245.

Gasper, D., 2010: The idea of human security. In: *Climate Change, Ethics and Human Security* [O'Brien, K., A. St. Clair, and B. Kristoffersen (eds)]. Cambridge University Press, Cambridge, UK, pp. 23-46.

Gaurav, K., R. Sinha, and P. Panda, 2011: The Indus flood of 2010 in Pakistan: a perspective analysis using remote sensing data. *Natural Hazards*, **59(3)**, 1815-1826.

Gausset, Q., 2005: Agro-pastoral conflicts in the Tikar Plain. In: *Beyond Territory and Scarcity: Exploring Conflicts over Natural Resource Management* [Guasset, Q., M. Whyte, and T. Birch-Thomsen (eds.)]. Nordiska Afrikainstitutet, Stockholm, Sweden, pp. 90-111.

Gearheard, S., M. Pocernich, R. Stewart, J. Sanguya, and H. Huntington, 2010: Linking Inuit knowledge and meteorological station observations to understand changing wind patterns at Clyde River, Nunavut. *Climatic Change*, **100(2)**, 267-294.

Geddes, A., W.N. Adger, N.W. Arnell, R. Black, and D.S.G. Thomas, 2012: Migration, environmental change, and the challenges of governance. *Environment and Planning C: Government and Policy*, **30**, 951-967.

Gemenne, F., 2011: Climate-induced population displacements in a 4C+ world. *Philosophical Transactions of the Royal Society A*, **369(1934)**, 182-195.

Gero, A., K. Méheux, and D. Dominey-Howes, 2011: Integrating community based disaster risk reduction and climate change adaptation: examples from the Pacific. *Natural Hazards and Earth System Science*, **11(1)**, 101-113.

Gila, O.A., A.U. Zaratiegui, and V.L. De Maturana Diéguez, 2011: Western Sahara: migration, exile and environment. *International Migration*, **49(Suppl. 1)**, e146-e163.

Gilman, N., D. Randall, and P. Schwartz, 2011: Climate change and security. In: *Oxford Handbook of Climate Change and Society* [Dryzek, J., R. Norgaard, and D. Schlossberg (eds).]. Oxford University Press: Oxford, UK and New York, NY, USA, pp. 251-266.

Glantz, M. and D. Jamieson, 2000: Societal response to Hurricane Mitch and intra- versus intergenerational equity issues: whose norms should apply? *Risk Analysis*, **20(6)**, 869-882.

Gleditsch, N.P., 2012: Whither the weather? Climate change and conflict. *Journal of Peace Research*, **49(1)**, 3-9.

Gómez-Baggethun, E., V. Reyes-García, P. Olsson, and C. Montes, 2012: Traditional ecological knowledge and community resilience to environmental extremes: a case study in Doñana, SW Spain. *Global Environmental Change*, **22(3)**, 640-650.

Goodhand, J., 2003: Enduring disorder and persistent poverty: a review of the linkages between war and chronic poverty. *World Development*, **31(3)**, 629-646.

Goulden, M., D. Conway, and A. Persechino, 2010: Adaptation to climate change in international river basins in Africa: a review. *Hydrological Sciences Journal*, **54(5)**, 805-828.

Gray, C.L., 2010: Gender, natural capital, and migration in the southern Ecuadorian Andes. *Environment and Planning A*, **42(3)**, 678-696.

Gray, C.L., 2011: Soil quality and human migration in Kenya and Uganda. *Global Environmental Change*, **21(2)**, 421-430.

Gray, C. and V. Mueller, 2012: Drought and population mobility in rural Ethiopia. *World Development*, **40(1)**, 134-145.

Green, D., L. Alexander, K. McInnes, J. Church, N. Nicholls, and N. White, 2010: An assessment of climate change impacts and adaptation for the Torres Strait Islands, Australia. *Climatic Change*, **102(3-4)**, 405-433.

Gregory, R. and W. Trousdale, 2009: Compensating aboriginal cultural losses: an alternative approach to assessing environmental damages. *Journal of Environmental Management*, **90(8)**, 2469-2479.

Grimm, N.B., S.H. Faeth, N.E. Golubiewski, C.L. Redman, J. Wu, X. Bai, and J.M. Briggs, 2008: Global change and the ecology of cities. *Science*, **319(5864)**, 756-760.

Hadipuro, W., 2007: Water supply vulnerability assessment for sustainable livelihood. *Journal of Environmental Assessment Policy and Management*, **9(1)**, 121-135.

Hagan, J. and J. Kaiser, 2011: The displaced and dispossessed of Darfur: explaining the sources of a continuing state-led genocide. *British Journal of Sociology*, **62(1)**, 1-25.

Haines, A, A.J. McMichael, K.R. Smith, I. Roberts, J. Woodcock, A. Markandya, B.G. Armstrong, D. Campbell-Lendrum, A.D. Dangour, M. Davies, N. Bruce, C. Tonne, M. Barrett, and P. Wilkinson, 2009: Public health benefits of strategies to reduce greenhouse-gas emissions: overview and implications for policy makers. *Lancet* **374(9707)**, 2104-2114.

Hall, J.W., E.P. Evans, E.C. Penning-Rowsell, P.B. Sayers, C.R. Thorne, and A.J. Saul, 2003: Quantified scenarios analysis of drivers and impacts of changing flood risk in England and Wales: 2030-2100. *Global Environmental Change Part B: Environmental Hazards*, **5(3-4)**, 51-65.

Hallegatte, S., 2012: A framework to investigate the economic growth impact of sea level rise. *Environmental Research Letters*, **7(1)**, 015604, doi:10.1088/1748-9326/7/1/015604.

Hallegatte, S., F. Henriet, and J. Corfee-Morlot, 2011: The economics of climate change impacts and policy benefits at city scale: a conceptual framework. *Climatic Change*, **104(1)**, 51-87.

Hanson, S., R. Nicholls, N. Ranger, S. Hallegatte, J. Corfee-Morlot, C. Herweijer, and J. Chateau, 2011: A global ranking of port cities with high exposure to climate extremes. *Climate Change*, **104(1)**, 89-111.

Harries, T. and E. Penning-Rowsell, 2011: Victim pressure, institutional inertia and climate change adaptation: the case of flood risk. *Global Environmental Change*, **21(1)**, 188-197.

Hassan, M.K.R., 2010: Urban environmental problems in cities of the Kurdistan region in Iraq. *Local Environment*, **15(1)**, 59-72.

Haug, R., 2002: Forced migration, processes of return and livelihood construction among pastoralists in Northern Sudan. *Disasters*, **26(1)**, 70-84.

Haywood, J.M., A. Jones, N. Bellouin, and D. Stephenson, 2013: Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall. *Nature Climate Change*, **3**, 660-665.

Hegre, H. and N. Sambanis, 2006: Sensitivity analysis of empirical results on civil war onset. *Journal of Conflict Resolution*, **50(4)**, 508-535.

Headey, D.D., 2013: The impact of the global food crisis on self-assessed food security. *World Bank Economic Review*, **27**, 1-27.

Hendrix, C.S. and S.M. Glaser, 2007: Trends and triggers: climate, climate change and civil conflict in Sub-Saharan Africa. *Political Geography*, **26(6)**, 695-715.

Hendrix, C.S. and I. Salehyan, 2012: Climate change, rainfall, and social conflict in Africa. *Journal of Peace Research*, **49(1)**, 35-50.

Henry, S., B. Schoumaker, and C. Beauchemin, 2004: The impact of rainfall on the first out-migration: a multi-level event-history analysis in Burkina Faso. *Population and Environment*, **25(5)**, 423-460.

Hertel, T.W. and S.D. Rosch, 2010: Climate change, agriculture, and poverty. *Applied Economic Perspectives and Policy*, **32(3)**, 355-385.

Hertel, T.W., M.B. Burke, and D.B. Lobell, 2010: The poverty implications of climate-induced crop yield changes by 2030. *Global Environmental Change*, **20(4)**, 577-585.

Heyd, T., 2008: Cultural responses to natural changes such as climate change. *Espace populations sociétés*, **1**, 83-88.

Hidalgo, F.D., S. Naidu, S. Nichter, and N. Richardson, 2010: Economic determinants of land invasions. *Review of Economics and Statistics*, **92(3)**, 505-523.

Hilson, G. and S. Van Bockstael, 2011: Diamond mining, rice farming and a 'Maggi cube': a viable survival strategy in rural Liberia? *Journal of International Development*, **23(8)**, 1042-1053.

Hitchcock, R.K., 2009: From local to global: perceptions and realities of environmental change among Kalahari San. In: *Anthropology and Climate Change: From Encounters to Actions* [Crate, S.A. and M. Nuttall (eds.)]. Left Coast Press, Walnut Creek, CA, USA, pp. 250-265.

Holland, M.M., C.M. Bitz, and B. Tremblay, 2006: Future abrupt reductions in the summer Arctic sea ice. *Geophysical Research Letters*, **33(23)**, L23503, doi:10.1029/2006GL028024.

Homann, S., B. Rischkowsky, J. Steinbach, M. Kirk, and E. Mathias, 2008: Towards endogenous livestock development: Borana pastoralists' responses to environmental and institutional changes. *Human Ecology*, **36(4)**, 503-520.

Hoogensen, G. and K. Stuvøy, 2006: Gender, resistance and human security. *Security Dialogue*, **37(2)**, 207-228.

Hori, M. and M.J. Schafer, 2010: Social costs of displacement in Louisiana after Hurricanes Katrina and Rita. *Population and Environment*, **31(1-3)**, 64-86.

Houghton, K.J., A.T. Vafeidis, B. Neumann, and A. Proelss, 2010: Maritime boundaries in a rising sea. *Nature Geoscience*, **3(12)**, 813-816.

Hovelsrud, G.K. and B. Smit (eds.), 2010: *Community Adaptation and Vulnerability in Arctic Regions.* Springer-Verlag Berlin Heidelberg, Germany, 369 pp.

Hovelsrud, G.K., H. Dannevig, J. West, and H. Amundsen, 2010a: Adaptation in fisheries and municipalities: three communities in northern Norway. In: *Community Adaptation and Vulnerability in Arctic Regions* [Hovelsrud, G.K. and B. Smit (eds.)]. Springer-Verlag Berlin Heidelberg, Germany, pp. 23-62.

Hovelsrud, G.K., J. White, M. Andrachuk, and B. Smit, 2010b: Community adaptation and vulnerability integrated. In: *Community Adaptation and Vulnerability in Arctic Regions* [Hovelsrud, G.K. and B. Smit (eds.)]. Springer-Verlag Berlin Heidelberg, Germany, pp. 335-348.

Hovelsrud, G., B. Poppel, B. Oort, and J. Reist, 2011: Arctic societies, cultures, and peoples in a changing cryosphere. *Ambio*, **40(1)**, 100-110.

Hovelsrud, G.K., J. West, and H. Dannevig, 2013: Fisheries, resource management and climate change: local perspectives of change in coastal communities in Northern Norway. In: *A Changing Environment for Human Security: Transformative Approaches to Research, Policy and Action* [Sygna, L., K. O'Brien, and J. Wolf (eds.)]. Routledge, London, pp. 135-146.

Howitt, R., O. Havnen, and S. Veland, 2012 Natural and unnatural disasters: responding with respect for indigenous rights and knowledges. *Geographical Research*, **50(1)**, 47-59.

Hsiang, S.M., K.C. Meng, and M.A. Cane, 2011: Civil conflicts are associated with the global climate. *Nature*, **476(7361)**, 438-441.

Hsiang, S., M. Burke, and E. Miguel, 2013: Quantifying the influence of climate on human conflict. *Science*, **341**, doi:10.1126/science.1235367.

Hugo, G., 2011: Lessons from past forced resettlement for climate change migration. In: *Migration and Climate Change* [Piguet, É., A. Pécoud, and P.d. Guchteneire (eds.)]. United Nations Educational, Scientific and Cultural Organization (UNESCO), Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 260-288.

Hulme, M., 2008: The conquering of climate: discourses of fear and their dissolution. *Geographical Journal*, **174(1)**, 5-16.

Humphreys, S., 2010: *Human Rights and Climate Change.* International Council on Human Rights Policy, Cambridge University Press, Cambridge, UK and New York, NY, USA, 348 pp.

Hunter, L.M. and E. David, 2011: Displacement, climate change and gender. In: *Migration and Climate Change.* [Piguet, É., A. Pécoud, and P.d. Guchteneire (eds.)]. United Nations Educational, Scientific and Cultural Organization (UNESCO), Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 306-330.

Huntington, H.P., 2011: Arctic science: the local perspective. *Nature*, **478(7368)**, 182-183.

Hurlimann, A. and S. Dolnicar, 2011: Voluntary relocation – an exploration of Australian attitudes in the context of drought, recycled and desalinated water. *Global Environmental Change*, **21(3)**, 1084-1094.

Ifejika Speranza, C., B. Kiteme, and U. Wiesmann, 2008: Droughts and famines: the underlying factors and the causal links among agro-pastoral households in semi-arid Makueni district, Kenya. *Global Environmental Change*, **18(1)**, 220-233.

Inglehart, R.F. and P. Norris, 2012: The Four Horsemen of the Apocalypse: understanding human security. *Scandinavian Political Studies*, **35(1)**, 71-96.

Ingram, K.T., M.C. Roncoli, and P.H. Kirshen, 2002: Opportunities and constraints for farmers of west Africa to use seasonal precipitation forecasts with Burkina Faso as a case study. *Agricultural Systems*, **74(3)**, 331-349.

Ivanic, M., W. Martin, and H. Zaman, 2012: Estimating the short-run poverty impacts of the 2010-11 surge in food prices. *World Development*, **40(11)**, 2302-2317.

Jacka, J., 2009: Global averages, local extremes: the subtleties and complexities of climate change in Papua New Guinea. In: *Anthropology and Climate Change: From Encounters to Actions* [Crate, S.A. and M. Nuttall (eds.)]. Left Coast Press, Walnut Creek, CA, USA, pp. 197-208.

Jakobeit, C. and C. Methmann, 2012: 'Climate refugees' as dawning catastrophe? A critique of the dominant quest for numbers. In: *Climate Change, Human Security and Violent Conflict: Challenges for Societal Stability* [Scheffran, J., M. Brzoska, H.G. Brauch, P.M. Link, and J. Schilling (eds.)]. Springer-Verlag, Berlin, Heidelberg, Germany, pp. 301-314.

Jensen, D. and S. Lonergan (eds.), 2013: *Assessing and Restoring Natural Resources in Post-Conflict Peacebuilding.* Routledge, Abingdon, UK and New York, NY, USA, 515 pp.

Johnson, C.A., 2012: Governing climate displacement: the ethics and politics of human resettlement. *Environmental Politics*, **21(2)**, 308-328.

Johnstone, S. and J. Mazo, 2011: Global warming and the Arab Spring. *Survival*, **53(2)**, 11-17.

Jones, P.G. and P.K. Thornton 2003: The potential impacts of climate change on maize production in Africa and Latin America in 2055. *Global Environmental Change*, **13**, 51-59.

Jones, P.G. and P.K. Thornton, 2009: Croppers to livestock keepers: livelihood transitions to 2050 in Africa due to climate change. *Environmental Science and Policy*, **12(4)**, 427-437.

Jülich, S., 2011: Drought triggered temporary migration in an East Indian village. *International Migration*, **49(Suppl. 1)**, e189-e199.

Kabubo-Mariara, J., 2009: Global warming and livestock husbandry in Kenya: impacts and adaptations. *Ecological Economics*, **68(7)**, 1915-1924.

Kainuma, M., Y. Matsuoka, T. Morita, T. Masui, and K. Takahashi, 2004: Analysis of global warming stabilization scenarios: the Asian-Pacific integrated model. *Energy Economics*, **26(4)**, 709-719.

Kalanda-Joshua, M., C. Ngongondo, L. Chipeta, and F. Mpembeka, 2011: Integrating indigenous knowledge with conventional science: enhancing localised climate and weather forecasts in Nessa, Mulanje, Malawi. *Physics and Chemistry of the Earth, Parts A/B/C*, **36(14-15)**, 996-1003.

Kaldor, M., 2007: *Human Security.* Polity Press, Cambridge, UK and Malden, MA, USA, 228 pp.

Kalikoski, D.C., P. Quevedo Neto, and T. Almudi, 2010: Building adaptive capacity to climate variability: the case of artisanal fisheries in the estuary of the Patos Lagoon, Brazil. *Marine Policy*, **34(4)**, 742-751.

Kartiki, K., 2011: Climate change and migration: a case study from rural Bangladesh. *Gender & Development*, **19(1)**, 23-38.

Keen, D.J., 2008: *Complex Emergencies.* Polity Press, Cambridge, UK and Malden, MA, USA, 293 pp.

Keith, D., 2000: Geoengineering the climate: history and prospect. *Annual Review of Energy Environment*, **25**, 245-284.

Kesavan, P.C. and M.S. Swaminathan, 2006: Managing extreme natural disasters in coastal areas. *Philosophical Transactions of the Royal Society of London A*, **364(1845)**, 2191-2216.

Keskitalo, E.C.H., 2009: Governance in vulnerability assessment: the role of globalising decision-making networks in determining local vulnerability and adaptive capacity. *Mitigation and Adaptation Strategies for Global Change*, **14(2)**, 185-201.

Kevane, M. and L. Gray, 2008: Darfur: rainfall and conflict. *Environmental Research Letters*, **3(3)**, 034006, doi:10.1088/1748-9326/3/3/034006.

Keywood, M., M. Kanakidou, A. Stohl, F. Dentener, G. Grassi, C.P. Meyer, K. Torseth, D. Edwards, A. Thompson, U. Lohmann, and J. Burrows, 2013: Fire in the air: biomass burning impacts in a change climate. *Critical Reviews in Environmental Science and Technology*, **43(1)**, 40-83.

King, D.N.T., J. Goff, and A. Skipper, 2007: Māori environmental knowledge and natural hazards in Aotearoa-New Zealand. *Journal of the Royal Society of New Zealand*, **37(2)**, 59-73.

King, D., 2008: Reducing hazard vulnerability through local government engagement and action. *Natural Hazards*, **47(3)**, 497-508.

King, M.D.B. and J. Gulledge, 2013: Climate change and energy security: an analysis of policy research. *Climatic Change*, doi:10.1007/s10584-013-0895-0.

Kingsbury, D., 2007: Peace processes in Aceh and Sri Lanka: a comparative assessment. *Security Challenges Journal*, **3(2)**, 93-112.

Klein, R.J., E.L.F. Schipper, and S. Dessai, 2005: Integrating mitigation and adaptation into climate and development policy: three research questions. *Environmental Science & Policy*, **8(6)**, 579-588.

Kniveton, D., C. Smith, and S. Wood, 2011: Agent-based model simulations of future changes in migration flows for Burkina Faso. *Global Environmental Change*, **21(Suppl. 1)**, S34-S40.

Kniveton, D.R., C.D. Smith, and R. Black, 2012: Emerging migration flows in a changing climate in dryland Africa. *Nature Climate Change*, **2**, 444-447.

Knox J.H., 2009: Linking human rights and climate change at the United Nations. *Harvard Environmental Law Review*, **33**, 477-498.

Kofinas, G. and the communities of Aklavik, Arctic Village, Old Crow, and Fort McPherson, 2002: Community contributions to ecological monitoring: knowledge co-production in the U.S.-Canada Arctic borderlands. In: *The Earth is Faster Now: Indigenous Observations of Arctic Environmental Change* [Krupnik, I. and D. Jolly (eds.)]. Arctic Research Consortium of the USA in cooperation with the Arctic Studies Center, Smithsonian Institution, ARCUS, Fairbanks, Alaska, USA, pp. 54-91.

Kolmannskog, V., 2010: Climate change, human mobility, and protection: initial evidence from Africa. *Refugee Survey Quarterly*, **29(3)**, 103-119.

Koubi, V., T. Bernauer, A. Kalbhenn, and G. Spilker, 2012: Climate variability, economic growth, and civil conflict. *Journal of Peace Research*, **49(1)**, 113-127.

Krause, K. and O. Jütersonke, 2005: Peace, security and development in post-conflict environments. *Security Dialogue*, **36(4)**, 447-462.

Kuhlicke, C., 2010: The dynamics of vulnerability: some preliminary thoughts about the occurrence of 'radical surprises' and a case study on the 2002 flood (Germany). *Natural Hazards*, **55(3)**, 671-688.

Kuruppu, N. and D. Liverman, 2011: Mental preparation for climate adaptation: the role of cognition and culture in enhancing adaptive capacity of water management in Kiribati. *Global Environmental Change*, **21(2)**, 657-669.

Lal, P., 2010: Vulnerability to natural disasters: an economic analysis of the impact of the 2009 floods on the Fijian sugar belt. *Pacific Economic Bulletin*, **25(2, 2010)**, 62-77.

Landry, C.E., O. Bin, P. Hindsley, J.C. Whitehead, and K. Wilson, 2007: Going home: evacuation-migration decisions of Hurricane Katrina survivors. *Southern Economic Journal*, **74(2)**, 326-343.

Larsen, P.H., S. Goldsmith, O. Smith, M.L. Wilson, K. Strzepek, P. Chinowsky, and B. Saylor, 2008: Estimating future costs for Alaska public infrastructure at risk from climate change. *Global Environmental Change*, **18(3)**, 442-457.

Laukkonen, J., P.K. Blanco, J. Lenhart, M. Keiner, B. Cavric, and C. Kinuthia-Njenga, 2009: Combining climate change adaptation and mitigation measures at the local level. *Habitat International*, **33(3)**, 287-292.

Le, T.V.H., H.N. Nguyen, E. Wolanski, T.C. Tran, and S. Haruyama, 2007: The combined impact on the flooding in Vietnam's Mekong River delta of local man-made structures, sea level rise, and dams upstream in the river catchment. *Estuarine, Coastal and Shelf Science*, **71**, 110-116.

Leary, N., C. Conde, J. Kulkarni, A. Nyong, and J. Pulhin (eds.), 2008: *Climate Change and Vulnerability.* Earthscan, London, UK and Washington, DC, USA, 428 pp.

Lefale, P., 2010: Ua 'afa le Aso Stormy weather today: traditional ecological knowledge of weather and climate. The Samoa experience. *Climatic Change*, **100(2)**, 317-335.

Leichenko, R. and K. O'Brien, 2008: *Environmental Change and Globalization: Double Exposures.* Oxford University Press, New York, NY, USA, 192 pp.

Lilleør, H.B. and K. Van den Broeck, 2011: Economic drivers of migration and climate change in LDCs. *Global Environmental Change: Human and Policy Dimensions*, **21(Suppl. 1)**, S70-S81.

Lind, J. and S. Eriksen, 2006: The impacts of conflict on household coping strategies: evidence from Turkana and Kitui Districts in Kenya. *Die Erde*, **137(3)**, 249-270.

Lindsell, J.A., E. Klop, and A.M. Siaka, 2011: The impact of civil war on forest wildlife in West Africa: mammals in Gola Forest, Sierra Leone. *Oryx*, **45(1)**, 69-77.

Lindsey, P.A., S.S. Romanach, C.J. Tambling, K. Chartier, and R. Groom, 2011: Ecological and financial impacts of illegal bushmeat trade in Zimbabwe. *Oryx*, **45(1)**, 96-111.

Linneroth-Bayer, J. and A. Vári, 2008: Extreme weather and burden sharing in Hungary. In: *Fairness in Adaptation to Climate Change* [Adger, W.N., J. Paavola, S. Huq, and M.J. Mace (eds.)]. MIT Press, Cambridge MA, USA, pp. 229-259.

Lipset, D., 2011: The tides: masculinity and climate change in coastal Papua New Guinea. *Les Marées: Masculinité et Changement Climatique sur les Côtes de Papouasie-Nouvelle-Guinée*, **17(1)**, 20-43.

López-Carr, D., 2012: Agro-ecological drivers of rural out-migration to the Maya Biosphere Reserve, Guatemala. *Environmental Research Letters*, **7(4)**, 045603, doi:10.1088/1748-9326/7/4/045603.

Lujala, P. and S. Rustad (eds.), 2011: *High-Value Natural Resources and Post-Conflict Peacebuilding*. Earthscan, Abingdon, UK and New York, NY, USA, 688 pp.

Lusthaus, J., 2010: Shifting sands: sea level rise, maritime boundaries, and inter-state conflict. *Politics*, **30(2)**, 113-118.

Lynn, K., J. Daigle, J. Hoffman, F. Lake, N. Michelle, D. Ranco, C. Viles, G. Voggesser, and P. Williams, 2013: The impacts of climate change on tribal traditional foods. *Climatic Change*, **120(3)**, 545-556, doi:10.1007/s10584-013-0736-1.

Maaskant, B., S.N. Jonkman, and L.M. Bouwer, 2009: Future risk of flooding: an analysis of changes in potential loss of life in South Holland (The Netherlands). *Environmental Science and Policy*, **12(2)**, 157-169.

MacNeil, M.A., N.A.J. Graham, J.E. Cinner, N.K. Dulvy, P.A. Loring, S. Jennings, N.V.C. Polunin, A.T. Fisk, and T.R. McClanahan, 2010: Transitional states in marine fisheries: adapting to predicted global change. *Philosophical Transactions of the Royal Society B*, **365(1558)**, 3753-3763.

Mahoney, C.O. and T.M. Pinedo, 2007: Human security in communities in Costa Rica and the United States. *Journal of Social Issues*, **63(2)**, 353-368.

Maldonado, J., C. Shearer, R. Bronen, K. Peterson, and H. Lazrus, 2013: The impact of climate change on tribal communities in the US: displacement, relocation, and human rights. *Climatic Change*, **120(3)**, 601-614, doi:10.1007/s10584-013-0746-z.

Marfai, M., L. King, J. Sartohadi, S. Sudrajat, S. Budiani, and F. Yulianto, 2008: The impact of tidal flooding on a coastal community in Semarang, Indonesia. *The Environmentalist*, **28(3)**, 237-248.

Marin, A., 2010: Riders under storms: contributions of nomadic herders' observations to analysing climate change in Mongolia. *Global Environmental Change*, **20(1)**, 162-176.

Marino, E., 2012: The long history of environmental migration: assessing vulnerability construction and obstacles to successful relocation in Shishmaref, Alaska. *Global Environmental Change*, **22(2)**, 374-381.

Marino, E. and J. Ribot, 2012: Adding insult to injury: climate change and the inequities of climate intervention. *Global Environmental Change*, **22(2)**, 323-328.

Mark, B., G. Bury, J. McKenzie, A. French, and M. Baraer, 2010: Climate change and tropical Andean glacier recession: evaluating hydrologic changes and livelihood vulnerability in the Cordillera Blanca, Peru. *Annals of the Association of American Geographers*, **100(4)**, 794-805.

Marshall, N.A., 2011: Assessing resource dependency on the rangelands as a measure of climate sensitivity. *Society and Natural Resources*, **24(10)**, 1105-1115.

Marshall, N.A., S.E. Park, W.N. Adger, K. Brown, and S.M. Howden, 2012: Transformational capacity and the influence of place and identity. *Environmental Research Letters*, **7(3)**, 034022, doi:10.1088/1748-9326/7/3/034022.

Martin, S., 2009: Climate change, migration, and governance. *Global Governance*, **16(3)**, 397-414.

Martin, S.F., 2012: Environmental change and migration: legal and political frameworks. *Environment and Planning C: Government and Policy*, **30(6)**, 1045-1060.

Massey, D.S., W.G. Axinn, and D.J. Ghimire, 2010: Environmental change and out-migration: evidence from Nepal. *Population and Environment*, **32(2)**, 109-136.

Matthew, R.A., J. Barnett, B. McDonald, and K.L. O'Brien (eds.), 2010: *Global Environmental Change and Human Security: Understanding Environmental Threats to Wellbeing and Livelihoods.* MIT Press, Cambridge, MA, USA, 327 pp.

Mazo, J., 2009: Climate change and security. *The Adelphi Papers*, **49(409)**, 73-86.

McAdam, J., 2011: Refusing refuge in the Pacific: deconstructing climate-induced displacement in international law. In: *Migration and Climate Change* [Piguet, É., A. Pécoud, and P.d. Guchteneire (eds.)]. United Nations Educational, Scientific and Cultural Organization (UNESCO), Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 102-137.

McDonald-Wilmsen, B. and M. Webber, 2010: Dams and displacement: raising the standards and broadening the research agenda. *Water Alternatives*, **3(2)**, 142-161.

McEvoy, J. and M. Wilder, 2012: Discourse and desalination: potential impacts of proposed climate change adaptation interventions in the Arizona-Sonora border region. *Global Environmental Change*, **22(2)**, 353-363.

McLeman, R., 2009: Climate change and adaptive human migration: lessons from rural North America. In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, W.N., I. Lorenzoni, and K. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 296-310.

McLeman, R.A. and L.M. Hunter, 2010: Migration in the context of vulnerability and adaptation to climate change: insights from analogues. *Wiley Interdisciplinary Reviews: Climate Change*, **1(3)**, 450-461.

McLeman, R.A. and S.K. Ploeger, 2012: Soil and its influence on rural drought migration: insights from Depression-era Southwestern Saskatchewan, Canada. *Population & Environment*, **33(4)**, 304-332.

McLeman, R. and B. Smit, 2006: Migration as an adaptation to climate change. *Climatic Change*, **76(1)**, 31-53.

McMichael, C., J. Barnett, and A.J. McMichael, 2012: An ill wind? Climate change, migration, and health. *Environmental Health Perspectives*, **120(5)**, 646-654.

McNamara, K.E. and C. Gibson, 2009: 'We do not want to leave our land': Pacific ambassadors at the United Nations resist the category of 'climate refugees'. *Geoforum*, **40(3)**, 475-483.

McNeeley, S.M., 2012: Examining barriers and opportunities for sustainable adaptation to climate change in Interior Alaska. *Climatic Change*, **111(3-4)**, 835-857.

McSweeney, K. and O.T. Coomes, 2011: Climate-related disaster opens a window of opportunity for rural poor in northeastern Honduras. *Proceedings of the National Academy of Sciences of the United States of America*, **108(13)**, 5203-5208.

Mehrotra, S., C. Rosenzweig, and W.D. Solecki, 2011: Cities, disaster and climate risk. In: *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, C., W.D. Solecki, S.A. Hammer, and S. Mehrotra (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 15-42.

Melick, D., 2010: Credibility of REDD and experiences from Papua New Guinea. *Conservation Biology*, **24(2)**, 359-361.

Mendelsohn, R., W. Morrison, M.E. Schlesinger, and N.G. Andronova, 2000: Country-specific market impacts of climate change. *Climatic Change*, **45(3)**, 553-569.

Mendelsohn, R., A. Dinar, and L. Williams, 2006: The distributional impact of climate change on rich and poor countries. *Environment and Development Economics*, **11(2)**, 159-178.

Mendelsohn, R., A. Basist, P. Kurukulasuriya, and A. Dinar, 2007: Climate and rural income. *Climatic Change*, **81(1)**, 101-118.

Mercer, J., I. Kelman, S. Suchet-Pearson, and K. Lloyd, 2009: Integrating indigenous and scientific knowledge bases for disaster risk reduction in Papua New Guinea. *Geografiska Annaler: Series B, Human Geography*, **91(2)**, 157-183.

Mercer, K.L., H.R. Perales, and J.D. Wainwright, 2012: Climate change and the transgenic adaptation strategy: smallholder livelihoods, climate justice, and maize landraces in Mexico. *Global Environmental Change*, **22(2)**, 495-504.

Mertz, O., C. Mbow, A. Reenberg, and A. Diouf, 2009: Farmers' perceptions of climate change and agricultural adaptation strategies in rural Sahel. *Environmental Management*, **43(5)**, 804-816.

Messer, E. and M.J. Cohen, 2011: Understanding and responding to the links between conflict and hunger. *Development in Practice*, **21(4-5)**, 481-487.

Meze-Hausken, E., 2000: Migration caused by climate change: how vulnerable are people in dryland areas? *Mitigation and Adaptation Strategies for Global Change*, **5(4)**, 379-406.

Mideksa, T.K., 2010: Economic and distributional impacts of climate change: the case of Ethiopia. *Global Environmental Change*, **20(2)**, 278-286.

Miguel, E., S. Satyanath, and E. Sergenti, 2004: Economic shocks and civil conflict: an instrumental variables approach. *Journal of Political Economy*, **112(4)**, 725-753.

Molony, T. and J. Smith, 2010: Biofuels, food security, and Africa. *African Affairs*, **109(436)**, 489-498.

Molua, E.L., J. Benhin, J. Kabubo-Mariara, M. Ouedraogo, and S. El-Marsafawy, 2010: Global climate change and vulnerability of African agriculture: implications for resilience and sustained productivity. *Quarterly Journal of International Agriculture*, **49(3)**, 183-211.

Mortreux, C. and J. Barnett, 2009: Climate change, migration and adaptation in Funafuti, Tuvalu. *Global Environmental Change*, **19(1)**, 105-112.

Moser, S.C., 2012: Adaptation, mitigation, and their disharmonious discontents: an essay. *Climatic Change*, **111(2)**, 165-175.

Mubaya, C.P., J. Njuki, E.P. Mutsvangwa, F.T. Mugabe, and D. Nanja, 2012: Climate variability and change or multiple stressors? Farmer perceptions regarding threats to livelihoods in Zimbabwe and Zambia. *Journal of Environmental Management*, **102**, 9-17.

Murtinho, F. and T.M. Hayes, 2012: Adaptation in resource-dependent communities: a call for greater methodological clarity in adaptation field research. *Society & Natural Resources*, **25(5)**, 513-522.

Mutter, J., 2010: Disasters widen the rich-poor gap, *Nature*, **466**, 1042.

Myers, C.A., T. Slack, and J. Singelmann, 2008: Social vulnerability and migration in the wake of disaster: the case of Hurricanes Katrina and Rita. *Population and Environment*, **29(6)**, 271-291.

Næss, L.O., I.T. Norland, W.M. Lafferty, and C. Aall, 2006: Data and processes linking vulnerability assessment to adaptation decision-making on climate change in Norway. *Global Environmental Change*, **16(2)**, 221-233.

Najam, A., 2003: Environment and security: exploring the links. In: *Environment, Development, and Human Security: Perspectives from South Asia* [Najam, A. (ed.)]. University Press of America, Lanham, MD, USA, pp. 1-24.

Nakashima, D. and M. Rou´e, 2002: Indigenous knowledge, peoples and sustainable practice. In: *Social and Economic Dimensions of Global Environmental Change* [Timmerman, M.P. (ed.)]. John Wiley, Chichester, UK, pp. 314-324.

Nakashima, D.J., K. Galloway McLean, H.D. Thulstrup, A. Ramos Castillo, and J.T. Rubis, 2012: *Weathering Uncertainty: Traditional Knowledge for Climate Change Assessment and Adaptation.* United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris, France, and United Nations University (UNU), Darwin, Australia, 120 pp.

National Research Council, 2012: *Himalayan Glaciers: Climate Change, Water Resources, and Water Security*. National Academies Press, Washington, DC, USA, 144 pp.

New, M., D. Liverman, H. Schroder, and K. Anderson, 2011: Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications. *Philosophical Transactions of the Royal Society A*, **369(1934)**, 6-19.

Nicholls, R.J., N. Marinova, J.A. Lowe, S. Brown, P. Vellinga, D.d. Gusmão, J. Hinkel, and R.S.J. Tol, 2011: Sea-level rise and its possible impacts given a 'beyond 4°C world' in the twenty-first century. *Philosophical Transactions of the Royal Society A*, **369 (1934)**, 161-181.

Nielsen, J.Ø. and A. Reenberg, 2010: Cultural barriers to climate change adaptation: a case study from northern Burkina Faso. *Global Environmental Change*, **20(1)**, 142-152.

Nielsen, J.Ø. and A. Reenberg, 2012: Exploring causal relations: the societal effects of climate change. *Danish Journal of Geography*, **112(2)**, 89-92.

Nigel, J., 2009: Livelihoods in a conflict setting. *Norsk Geografisk Tidsskrift – Norwegian Journal of Geography*, **63(1)**, 23-34.

Norgaard, K.M., 2011: *Living in Denial: Climate Change, Emotions, and Everyday Life.* MIT Press, Cambridge, MA, USA, 278 pp.

Nunn, P.D., 2000: Coastal changes over the past 200 years around Ovalau and Moturiki Islands, Fiji: implications for coastal zone management. *Australian Geographer*, **31(1)**, 21-39.

Nursey-Bray, M., G.T. Pecl, S. Frusher, C. Gardner, M. Haward, A.J. Hobday, S. Jennings, A.E. Punt, H. Revill, and I. van Putten, 2012: Communicating climate change: climate change risk perceptions and rock lobster fishers, Tasmania. *Marine Policy*, **36(3)**, 753-759.

Nuttall, M., 2009: Living in a world of movement human resilience to environmental instability in Greenland. In: *Anthropology and Climate Change: From Encounters to Actions* [Crate, S.A. and M. Nuttall (eds.)]. Left Coast Press, Walnut Creek, CA, USA, pp. 292-310.

Nyong, A., F. Adesina, and B. Osman Elasha, 2007: The value of indigenous knowledge in climate change mitigation and adaptation strategies in the African Sahel. *Mitigation and Adaptation Strategies for Global Change*, **12(5)**, 787-797.

Oberthür, T., E. Barrios, S. Cook, H. Usma, and G. Escobar, 2004: Increasing the relevance of scientific information in hillside environments through understanding of local soil management in a small watershed of the Colombian Andes. *Soil Use and Management*, **20(1)**, 23-31.

O'Brien, K., 2006: Are we missing the point? Global environmental change as an issue of human security. *Global Environmental Change*, **16(1)**, 1-3.

O'Brien, K.L. and J. Wolf, 2010: A values-based approach to vulnerability and adaptation to climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **1(2)**, 232-242.

O'Brien, K., R. Leichenko, U. Kelkar, H. Venema, G. Aandahl, H.Tompkins, A. Javed, S. Bhadwal, S. Barg, L. Nygaard, and J. West, 2004: Mapping vulnerability to multiple stressors: climate change and globalization in India. *Global Environmental Change*, **14**, 303-313.

O'Brien, K., A.L. St Clair, and B. Kristoffersen (eds.), 2010: *Climate Change, Ethics and Human Security.* Cambridge University Press, Cambridge, UK and New York, NY, USA, 247 pp.

O'Loughlin, J., F.D.W. Witmer, A.M. Linke, A. Laing, A. Gettelman, and J. Dudhia, 2012: Climate variability and conflict risk in East Africa, 1990-2009. *Proceedings of the National Academy of Sciences of the United States of America*, **109(45)**, 18344-18349.

Oels, A., 2013: Rendering climate change governable by risk: from probability to contingency. *Geoforum*, **45**, 17-29.

Oliver-Smith, A., 2011: Sea level rise, local vulnerability and involuntary migration. In: *Migration and Climate Change* [Piguet, É., A. Pécoud, and P.d. Guchteneire (eds.)]. United Nations Educational, Scientific and Cultural Organization (UNESCO), Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 160-185.

Olson, R.S. and V.T. Gawronski, 2010: From disaster event to political crisis: a "5C A" framework for analysis. *International Studies Perspectives*, **11(3)**, 205-221.

Oluoko-Odingo, A.A., 2011: Vulnerability and adaptation to food insecurity and poverty in Kenya. *Annals of the Association of American Geographers*, **101(1)**, 1-20, doi:10.1080/00045608.2010.532739.

Onta, N. and B.P. Resurreccion, 2011: The role of gender and caste in climate adaptation strategies in Nepal: emerging change and persistent inequalities in the far-western region. *Mountain Research and Development*, **31(4)**, 351-356.

Orlove, B.S., J.C.H. Chiang, and M.A. Cane, 2000: Forecasting Andean rainfall and crop yield from the influence of El Niño on Pleiades visibility. *Nature*, **403(6765)**, 68-71.

Orlove, B.S., E. Wiegandt, and B.H. Luckman (eds.), 2008: *Darkening Peaks: Glacier Retreat, Science, and Society*. University of California Press, Berkeley, CA, USA.

Orlove, B., C. Roncoli, M. Kabugo, and A. Majugu, 2010: Indigenous climate knowledge in southern Uganda: the multiple components of a dynamic regional system. *Climatic Change*, **100(2)**, 243-265.

Osbahr H., C. Twyman, W.N. Adger, and D.S.G. Thomas, 2010: Evaluating successful livelihood adaptation to climate variability and change in southern Africa. *Ecology and Society*, **15(2)**, 27.

Oswald Spring, Ú., 2008: *Gender and Disasters: Human, Gender and Environmental Security: A HUGE Challenge*. Studies of the University: Research, Counsel, Education No. 8/2008, United Nations University, Institute for Environment and Human Security, Bonn, Germany, 56 pp.

Oswald Spring, Ú., 2012: Can health be securitized? *Human Evolution*, **27(1-3)**, 21-29.

Oswald Spring, Ú., S.E. Serrano Oswald, A. Estrada Álvarez, F. Flores-Palacios, M. Ríos Everardo, H.G. Brauch, T.E. Ruíz Pantoja, C. Lemus Ramírez, A. Estrada Villareal, and M. Cruz, 2013: *Vulnerabilidad Social y Género entre Migrantes Ambientales*. El Centro Regional de Investigaciones Multidisciplinarias (CRIM), Dirección General de Asuntos del Personal Académico-Universidad Nacional Autónoma de México, Cuernavaca, Mexico, 820 pp.

Othman, Z., 2009: Human security concepts, approaches and debates in Southeast Asia. In: *Facing Global Environmental Change: Environmental, Human, Energy, Food, Health and Water Security Concepts* [Brauch, H.G., Ú. Oswald Spring, J. Grin, C. Mesjasz, P. Kameri-Mbote, N.C. Behera, B. Chourou, and H. Krummenacher (eds.)]. Springer-Verlag, Berlin, Heidelberg, Germany, pp. 1037-1047.

Owen, T., 2004: Human security – conflict, critique and consensus: colloquium remarks and a proposal for a threshold-based definition. *Security Dialogue*, **35(3)**, 373-387.

Owens, J., 2008: Environmental refugees, corrective justice and a system of compensation. *International Journal of Green Economics*, **2(3)**, 311-328.

Paavola, J., 2008: Livelihoods, vulnerability and adaptation to climate change in Morogoro, Tanzania. *Environmental Science and Policy*, **11(7)**, 642-654.

Paris, R., 2001: Human security: paradigm shift or hot air? *International Security*, **26(2)**, 87-102.

Parker, G., 2008: Crisis and catastrophe: the global crisis of the seventeenth century reconsidered. *American Historical Review*, **113(4)**, 1053-1079.

Parnell, S. and R. Walawege, 2011: Sub-Saharan African urbanisation and global environmental change. *Global Environmental Change*, **21(Suppl. 1)**, S12-S20.

Paul, B.K., 2005: Evidence against disaster-induced migration: the 2004 tornado in north-central Bangladesh. *Disasters*, **29(4)**, 370-385.

Paul, S.K. and J.K. Routray, 2010: Flood proneness and coping strategies: the experiences of two villages in Bangladesh. *Disasters*, **34**, 489-508.

Paul, S.K. and J.K. Routray, 2011: Household response to cyclone and induced surge in coastal Bangladesh: coping strategies and explanatory variables. *Natural Hazards*, **57(2)**, 477-499.

Pearce, T.D., J.D. Ford, G.J. Laidler, B. Smit, F. Duerden, M. Allarut, M. Andrachuk, S. Baryluk, A. Dialla, P. Elee, A. Goose, T. Ikummaq, E. Joamie, F. Kataoyak, E. Loring, S. Meakin, S. Nickels, K. Shappa, J. Shirley, and J. Wandel, 2009: Community collaboration and climate change research in the Canadian Arctic. *Polar Research*, **28(1)**, 10-27.

Peduzzi, P., H. Dao, C. Herold, and F. Mouton, 2009: Assessing global exposure and vulnerability towards natural hazards: the Disaster Risk Index. *Natural Hazards and Earth System Sci*ence, **9**, 1149-1159.

Pelling, M. and K. Dill, 2010: Disaster politics: tipping points for change in the adaptation of sociopolitical regimes. *Progress in Human Geography*, **34(1)**, 21-37.

Peluso, N.L. and M. Watts (eds.), 2001: *Violent Environments.* Cornell University Press, Ithaca, NY, USA, 453 pp.

Penning-Rowsell, E.C., P. Sultana, and P.M. Thompson, 2013: The 'last resort'? Population movement in response to climate-related hazards in Bangladesh. *Environmental Science & Policy*, **27(Suppl. 1)**, S44-S59.

Peras, R.J., J.M. Pulhin, R.D. Lasco, R.V.O. Cruz, and F.B. Pulhin, 2008: climate variability and extremes in the Pantabangan-Carranglan Watershed, Philippines: assessment of impacts and adaptation practices. *Journal of Environmental Science and Management*, **11(2)**, 14-31.

Perry, R. and U. Sumaila, 2007: Marine ecosystem variability and human community responses: the example of Ghana, West Africa. *Marine Policy*, **31(2)**, 125-134.

Petheram, L., K.K. Zander, B.M. Campbell, C. High, and N. Stacey, 2010: 'Strange changes': indigenous perspectives of climate change and adaptation in NE Arnhem Land (Australia). *Global Environmental Change*, **20(4)**, 681-692.

Phillips, M.R. and A.L. Jones, 2006: Erosion and tourism infrastructure in the coastal zone: problems, consequences and management. *Tourism Management*, **27(3)**, 517-524.

Piesse, J. and C. Thirtle, 2009: Three bubbles and a panic: an explanatory review of recent food commodity price events, *Food Policy*, **34**, 119-129.

Pietsch, J. and I. McAllister, 2010: Human security in Australia: public interest and political consequences. *Australian Journal of International Affairs*, **64(2)**, 225-244.

Piguet, É., 2010: Linking climate change, environmental degradation, and migration: a methodological overview. *Wiley Interdisciplinary Reviews: Climate Change*, **1(4)**, 517-524.

Piguet, É., 2013: From "primitive migration" to "climate refugees" – the curious fate of the natural environment in migration studies. *Annals of the Association of American Geographers*, **103(1)**, 148-162.

Piguet, É., A. Pécoud, and P. de Guchteneire (eds.), 2011: *Migration and Climate Change.* United Nations Educational, Scientific and Cultural Organization (UNESCO), Cambridge University Press, Cambridge, UK and New York, NY, USA, 442 pp.

Pike, I., 2004: The biosocial consequences of life on the run: a case study from Turkana District, Kenya. *Human Organization*, **63(2)**, 221-235.

Poku, N.K. and B. Sandkjaer, 2009: Human security in sub-Saharan Africa. In: *Facing Global Environmental Change: Environmental, Human, Energy, Food, Health and Water Security Concepts* [Brauch, H.G., Ú. Oswald Spring, J. Grin, C. Mesjasz, P. Kameri-Mbote, N.C. Behera, B. Chourou, and H. Krummenacher (eds.)]. Springer-Verlag, Berlin, Heidelberg, Germany, pp. 1057-1070.

Posner, E., 2007: Climate change and international human rights litigation: a critical appraisal. *University of Pennsylvania Law Review*, **155**, 1925-1925.

Preston, C.J., 2013: Ethics and geoengineering: reviewing the moral issues raised by solar radiation management and carbon dioxide removal. *Wiley Interdisciplinary Reviews: Climate Change*, **4**, 23-37.

Quinn, C.H., G. Ziervogel, A. Taylor, T. Takama, and F. Thomalla, 2011: Coping with multiple stresses in rural South Africa. *Ecology and Society*, **16(3)**, 2, www.ecologyandsociety.org/vol16/iss3/art2/.

Raddad, S., A.G. Salleh, and N. Samat, 2010: Determinants of agriculture land use change in Palestinian urban environment: urban planners at local governments perspective. *American-Eurasian Journal of Sustainable Agriculture*, **4(1)**, 30-38.

Raleigh, C., 2011: The search for safety: the effects of conflict, poverty and ecological influences on migration in the developing world. *Global Environmental Change*, **21(Suppl. 1)**, S82-S93.

Raleigh, C. and D. Kniveton, 2012: Come rain or shine: an analysis of conflict and climate variability in East Africa. *Journal of Peace Research*, **49(1)**, 51-64.

Rammohan, A. and M. Johar, 2009: The determinants of married women's autonomy in Indonesia. *Feminist Economics*, **15(4)**, 31-55.

Rattenbury, K., K. Kielland, G. Finstad, and W. Schneider, 2009: A reindeer herder's perspective on caribou, weather and socio-economic change on the Seward Peninsula, Alaska. *Polar Research*, **28(1)**, 71-88.

Rautela, P., 2005: Indigenous technical knowledge inputs for effective disaster management in the fragile Himalayan ecosystem. *Disaster Prevention and Management*, **14(2)**, 233-241.

Ravera, F., D. Tarrasón, and E. Simelton, 2011: Envisioning adaptive strategies to change: participatory scenarios for agropastoral semiarid systems in Nicaragua. *Ecology and Society*, **16(1)**, 20, www.ecologyandsociety.org/vol16/iss1/art20/.

Renaud, F.G., O. Dun, K. Warner, and J. Bogardi, 2011: A decision framework for environmentally induced migration. *International Migration*, **49(Suppl. s1)**, e5-e29, doi:10.1111/j.1468-2435.2010.00678.x.

Revi, A., 2005: Lessons from the deluge: priorities for multi-hazard risk mitigation. *Economic and Political Weekly*, **40(36)**, 3911-3916.

Ribot, J., 2011: Vulnerability before adaptation: toward transformative climate action. *Global Environmental Change*, **21(4)**, 1160-1162.

Ricke, K.L., M.G. Morgan, and M.R. Allen, 2010: Regional climate response to solar-radiation management. *Nature Geoscience*, **3**, 537-541.

Robock, A., 2008: Whither geoengineering. *Science*, **320(5880)**, 1166-1167.

Rojas, A.F., 2009: Human security: a South American perspective. In: *Facing Global Environmental Change: Environmental, Human, Energy, Food, Health and Water Security Concepts* [Brauch, H.G., Ú. Oswald Spring, J. Grin, C. Mesjasz, P. Kameri-Mbote, N.C. Behera, B. Chourou, and H. Krummenacher (eds.)]. Springer-Verlag, Berlin, Heidelberg, Germany, pp. 1077-1086.

Roncoli, C., 2006: Ethnographic and participatory approaches to research on farmers' responses to climate predictions. *Climate Research*, **33(1)**, 81-99.

Roncoli, C., C. Jost, P. Kirshen, M. Sanon, K. Ingram, M. Woodin, L. Somé, F. Ouattara, B. Sanfo, C. Sia, P. Yaka, and G. Hoogenboom, 2009: From accessing to assessing forecasts: an end-to-end study of participatory climate forecast dissemination in Burkina Faso, West Africa. *Climatic Change*, **92(3-4)**, 433-460.

Roncoli, C., B.S. Orlove, M.R. Kabugo, and M.M. Waiswa, 2011: Cultural styles of participation in farmers' discussions of seasonal climate forecasts in Uganda. *Agriculture and Human Values*, **28(1)**, 123-138.

Rosenzweig, C., W.D. Solecki, S.A. Hammer, and S. Mehrotra (eds.), 2011: *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network*. Cambridge University Press, Cambridge, UK and New York, NY, USA, 286 pp.

Rowhani, P., O. Degomme, D. Guha-Sapir, and E.F. Lambin, 2011: Malnutrition and conflict in East Africa: the impacts of resource variability on human security. *Climatic Change*, **105(1)**, 207-222.

Rudiak-Gould, P., 2012: Promiscuous corroboration and climate change translation: case from the Marshall Islands. *Global Environmental Change*, **22(1)**, 46-54.

Ruel, M.T., J.L. Garrett, C. Hawkes, and M.J. Cohen, 2010: The food, fuel, and financial crises affect the urban and rural poor disproportionately: a review of the evidence. *Journal of Nutrition*, **140(Suppl. 1)**, 170S-176S.

Rybråten, S. and G.K. Hovelsrud, 2010: Local effects of global climate change: differential experiences of sheep farmers and reindeer herders in Unjarga, Nesseby, a coastal Sámi Community in Northern Norway. In: *Community Adaptation and Vulnerability in Arctic Communities* [Hovelsrud, G.K. and B. Smit (eds.)]. Springer, Dordrecht, Netherlands, pp. 313-333.

Sabur, A.K.M.A., 2009: Theoretical perspective on human security: a South Asian view. In: *Facing Global Environmental Change: Environmental, Human, Energy, Food, Health and Water Security Concepts* [Brauch, H.G., Ú. Oswald Spring, J. Grin, C. Mesjasz, P. Kameri-Mbote, N.C. Behera, B. Chourou, and H. Krummenacher (eds.)]. Springer-Verlag, Berlin, Heidelberg, Germany, pp. 1003-1011.

Sadoff, C. and D. Grey, 2002: Beyond the river: the benefits of cooperation on international rivers. *Water Policy*, **5(4)**, 389-404.

Saldana-Zorrilla, S.O., 2008: Stakeholders' views in reducing rural vulnerability to natural disasters in Southern Mexico: hazard exposure and coping and adaptive capacity. *Global Environmental Change*, **18(4)**, 583-597.

Salick, J. and N. Ross, 2009: Traditional peoples and climate change. *Global Environmental Change*, **19(2)**, 137-139.

Sánchez-Cohen, I., Ú. Oswald Spring, G. Díaz Padilla, J. Cerano Paredes, M.A. Inzunza Ibarra, R. López López, and J. Villanueva Díaz, 2013: Forced migration, climate change, mitigation and adaptive policies in Mexico: some functional relationships. *International Migration*, **51**, 53-72.

Sánchez-Cortés, M. and E. Chavero, 2011: Indigenous perception of changes in climate variability and its relationship with agriculture in a Zoque community of Chiapas, Mexico. *Climatic Change*, **107(3-4)**, 363-389.

Scheffran, J. and A. Battaglini, 2011: Climate and conflicts: the security risks of global warming. *Regional Environmental Change*, **11**, 27-39.

Scheffran, J., M. Brzoska, H.G. Brauch, P.M. Link, and J. Schilling (eds.), 2012a: *Climate Change, Human Security and Violent Conflict: Challenges for Societal Stability.* Springer-Verlag Berlin Heidelberg, Germany, 868 pp.

Scheffran, J., M. Brzoska, J. Kominek, P.M. Link, and J. Schilling, 2012b: Disentangling the climate-conflict nexus: empirical and theoretical assessment of vulnerabilities and pathways. *Review of European Studies*, **4(5)**, 1-13.

Scheffran, J., M. Brzoska, J. Kominek, P.M. Link, and J. Schilling, 2012c: Climate change and violent conflict. *Science*, **336(6083)**, 869-871.

Scheffran, J., E. Marmer, and P. Sow, 2012d: Migration as a contribution to resilience and innovation in climate adaptation: social networks and co-development in Northwest Africa. *Applied Geography*, **33(1)**, 119-127

Schlenker, W. and D.B. Lobell, 2010: Robust negative impacts of climate change on African agriculture. *Environmental Research Letters*, **5(1)**, 014010, doi:10.1088/1748-9326/5/1/014010.

Schroeder, H., 2010: Agency in international climate negotiations: the case of indigenous peoples and avoided deforestation. *International Environmental Agreements: Politics, Law and Economics*, **10(4)**, 317-332.

Selin, H. and N.E. Selin, 2008: Indigenous peoples in international environmental cooperation: Arctic management of hazardous substances. *Review of European Community & International Environmental Law*, **17(1)**, 72-83.

Seto, K.C., 2011: Exploring the dynamics of migration to mega-delta cities in Asia and Africa: contemporary drivers and future scenarios. *Global Environmental Change*, **21(Suppl. 1)**, S94-S107.

Shah, A. and O.G. Sajitha, 2009: Dwindling forest resources and economic vulnerability among tribal communities in a dry, sub-humid region in India. *Journal of International Development*, **21(3)**, 419-432.

Shen, S. and F. Gemenne, 2011: Contrasted views on environmental change and migration: the case of Tuvaluan migration to New Zealand. *International Migration*, **49(Suppl. s1)**, e224-e242.

Shomar, B., 2011: Water scenarios in the Gaza Strip, Palestine: thirst, hunger and disease. *International Journal of Environmental Studies*, **68(4)**, 477-493.

Singleton, S., 2000: Cooperation or capture? The paradox of co-management and community participation in natural resource management and environmental policy-making. *Environmental Politics*, **9(2)**, 1-21.

Siurua, H. and J. Swift, 2002: Drought and *zud* but no famine (yet) in the Mongolian herding economy. *IDS Bulletin*, **33(4)**, 88-97.

Skoulikidis, N.T., 2009: The environmental state of rivers in the Balkans – a review within the DPSIR framework. *Science of the Total Environment*, **407(8)**, 2501-2516.

Slade, N., 2007: Climate change: the human rights implications for small island developing states. *Environmental Policy and Law*, **37**, 215-219.

Slettebak, R.T., 2012: Don't blame the weather! Climate-related natural disasters and civil conflict. *Journal of Peace Research*, **49(1)**, 163-176.

Smit, B., G.K. Hovelsrud, J. Wandel, and M. Andrachuk, 2010: Introduction to the CAVIAR Project and Framework. In: *Community Adaptation and Vulnerability in Arctic Regions* [Hovelsrud, G.K. and B. Smit (eds.)]. Springer Science, Dordrecht, Netherlands, pp. 1-22.

Smith, P.J., 2011: The geopolitics of climate change: power transitions, conflict and the future of military activities. *Conflict, Security and Development*, **11(3)**, 309-334.

Socolow, R.H. and A. Glaser, 2009: Balancing risks: nuclear energy and climate change. *Daedalus*, **138(4)**, 31-44.

Stadel, C., 2008: Resilience and adaptations of rural communities and agricultural land use in the tropical Andes: coping with environmental and socio-economic changes. *Pirineos*, **163**, 15-36.

Steinbruner, J., P. Stern, and J. Husbands (eds.), 2012: *Climate Change and Social Stress: Implications for Security Analysis*. Committee on Assessing the Impact of Climate Change on Social and Political Stresses, National Research Council, National Academies Press, Washington, DC, USA, 238 pp.

Stephenson, S.R., L.C. Smith, and J.A. Agnew, 2011: Divergent long-term trajectories of human access to the Arctic. *Nature Climate Change*, **1(3)**, 156-160.

Stern, N., 2007: *The Economics of Climate Change: The Stern Review.* Cambridge University Press, Cambridge, UK, 500 pp.

Stevens, K., L. Campbell, G. Urquhart, D. Kramer, and J. Qi, 2011: Examining complexities of forest cover change during armed conflict on Nicaragua's Atlantic Coast. *Biodiversity and Conservation*, **20(12)**, 2597-2613.

Stewart, F. and V. Fitzgerald (eds.), 2001: *The Economic and Social Consequences of Conflict: War and Underdevelopment.* Vol. 1, Oxford University Press, Oxford, UK and New York, NY, USA, 280 pp.

Stewart, F., C. Huang, and M. Wang, 2001: Internal wars in developing countries: an empirical overview of economic and social consequences. In: *The Economic and Social Consequences of Conflict: War and Underdevelopment* [Stewart, F. and V. Fitzgerald (eds.)]. Oxford University Press, Oxford, UK and New York, NY, USA, pp. 67-103.

Strauss, S., 2009: Global models, local risks: responding to climate change in the Swiss Alps. In: *Anthropology and Climate Change: From Encounters to Actions* [Crate, S.A. and M. Nuttall (eds.)]. Left Coast Press, Walnut Creek, CA, USA, pp. 166-174.

Strauss, S., 2012: Are cultures endangered by climate change? Yes, but…. *Wiley Interdisciplinary Reviews: Climate Change*, **3(4)**, 371-377.

Suarez, P., W. Anderson, V. Mahal, and T.R. Lakshman, 2005: Impacts of flooding and climate change on urban transportation: a system wide performance assessment of the Boston Metro Area. *Transportation Research Part D: Transport and Environment*, **10(3)**, 231-244.

Sudmeier-Rieux, K., S. Jaquet, M.H. Derron, M. Jaboyedoff, and S. Devkota, 2012: A case study of coping strategies and landslides in two villages of Central-Eastern Nepal. *Applied Geography*, **32(2)**, 680-690.

Sumaila, U.R., W.W.L. Cheung, V.W.Y. Lam, D. Pauly, and S. Herrick, 2011: Climate change impacts on the biophysics and economics of world fisheries. *Nature Climate Change*, **1**, 449-456.

Sunga, L.S., 2011: Does climate change kill people in Darfur? *Journal of Human Rights and the Environment*, **2(1)**, 64-85.

Sutherland, W.J., 2003: Parallel extinction risk and global distribution of languages and species. *Nature*, **423**, 276-279.

Sygna, L., K. O'Brien, and J. Wolf (eds.), 2013: *A Changing Environment for Human Security: Transformative Approaches to Research, Policy and Action*. Routledge, Abingdon, UK and New York, NY, USA, 469 pp.

Swain, S., 2012: Global climate change and challenges for international river agreements *International Journal of Sustainable Society*, **4**, **(1-2)**, 72-87.

Tabara, D., D. Saurí, and R. Cerdan, 2003: Forest fire risk management and public participation in changing socioenvironmental conditions: a case study in a Mediterranean region. *Risk Analysis*, **23(2)**, 249-260.

Tacoli, C., 2009: Crisis or adaptation? Migration and climate change in a context of high mobility. *Environment and Urbanization*, **21(2)**, 513-525.

Tang, K.K., D. Petrie, and D.S. Rao, 2009: The income-climate trap of health development: a comparative analysis of African and Non-African countries. *Social Science & Medicine*, **69(7)**, 1099-1106.

Tänzler, D., A. Maas, and A. Carius, 2010: Climate change adaptation and peace. *Wiley Interdisciplinary Reviews: Climate Change* **1(5)**, 741-750.

Taylor, R.G., B. Scanlon, P. Döll, M. Rodell, R. van Beek, Y. Wada, L. Longuevergne, M. Leblanc, J.S. Famiglietti, M. Edmunds, L. Konikow, T.R. Green, J. Chen, M. Taniguchi, M.F.P. Bierkens, A. MacDonald, Y. Fan, R.M. Maxwell, Y. Yechieli, J.J. Gurdak, D.M. Allen, M. Shamsudduha, K. Hiscock, P.J.-F. Yeh, I. Holman, and H. Treidel, 2013: Ground water and climate change. *Nature Climate Change* **3**, 322-329.

Theisen, O.M., 2012: Climate clashes? Weather variability, land pressure, and organized violence in Kenya, 1989-2004. *Journal of Peace Research*, **49(1)**, 81-96.
Theisen, O.M., H. Holtermann, and H. Buhaug, 2012: Climate wars? Assessing the claim that drought breeds conflict. *International Security*, **36(3)**, 79-106.
Theisen, O.M., N.P. Gleditsch, and H. Buhaug, 2013: Is climate change a driver of armed conflict? *Climatic Change*, **117(3)**, 613-625.
Themnér, L. and P. Wallensteen, 2012: Armed conflicts, 1946-2011. *Journal of Peace Research*, **49(4)**, 565-575.
Thurlow, J., T. Zhu, and X. Diao, 2012: Current climate variability and future climate change: estimated growth and poverty impacts for Zambia. *Review of Development Economics* **16**, 394-411.
Tignino, M., 2011: The right to water and sanitation in post-conflict peacebuilding. *Water International*, **36(2)**, 242-249.
Tingley, D., J. Ásmundsson, E. Borodzicz, A. Conides, B. Drakeford, I. Rúnar Eðvarðsson, D. Holm, K. Kapiris, S. Kuikka, and B. Mortensen, 2010: Risk identification and perception in the fisheries sector: comparisons between the Faroes, Greece, Iceland and UK. *Marine Policy*, **34(6)**, 1249-1260.
Tir, J. and D.M. Stinnett, 2012: Weathering climate change: can institutions mitigate international water conflict? *Journal of Peace Research*, **49(1)**, 211-225.
Tol, R.S.J. and S. Wagner, 2010: Climate change and violent conflict in Europe over the last millennium. *Climatic Change*, **99**, 65-79.
Tolossa, D., 2008: Livelihood transformation from pastoralism to agro-pastoralism as an adaptation strategy among the Urrane of north-eastern Ethiopia. *Quarterly Journal of International Agriculture*, **2**, 145-165.
Tompkins, E.L., L.A. Hurlston, and W. Poortinga, 2009: Foreignness as a constraint on learning: the impact of migrants on disaster resilience in small islands. *Environmental Hazards*, **8(4)**, 263-277.
Trombetta, M.J., 2012: Climate change and the environmental conflict discourse. In: *Climate Change, Human Security and Violent Conflict: Challenges for Societal Stability* [Scheffran, J., M. Brzoska, H.G. Brauch, P.M. Link, and J. Schilling (eds.)]. Springer-Verlag, Berlin, Heidelberg, Germany, pp. 151-164.
Trotman, A., R.M. Gordon, S.D. Hutchinson, R. Singh, and D. McRae-Smith, 2009: Policy responses to global environmental change impacts on food availability and affordability in the Caribbean community. *Environmental Science and Policy*, **12(4)**, 529-541.
Tunstall, S., S. Tapsell, C. Green, P. Floyd, and C. George, 2006: The health effects of flooding: social research results from England and Wales. *Journal of Water and Health*, **4**, 365-380.
Turner, N.J. and H. Clifton, 2009: "It's so different today": climate change and indigenous lifeways in British Columbia, Canada. *Global Environmental Change*, **19(2)**, 180-190.
Tyler, N.J.C., J.M. Turi, M.A. Sundset, K. Strøm Bull, M.N. Sara, E. Reinert, N. Oskal, C. Nellemann, J.J. McCarthy, S.D. Mathiesen, M.L. Martello, O.H. Magga, G.K. Hovelsrud, I. Hanssen-Bauer, N.I. Eira, I.M.G. Eira, and R.W. Corell, 2007: Saami reindeer pastoralism under climate change: applying a generalized framework for vulnerability studies to a sub-Arctic social-ecological system. *Global Environmental Change*, **17(2)**, 191-206.
UN-HABITAT, 2011: *Cities and Climate Change: Global Report on Human Settlements 2011.* United Nations Human Settlements Programme, Earthscan, London, UK and Washington, DC, USA, 279 pp.
UNDP, 1994: *Human Development Report 1994: New Dimensions of Human Security*. Oxford University Press, New York, NY, USA, 226 pp.
UNDP, 2007: *Human Development Report 2007/2008: Fighting Climate Change: Human Solidarity in a Divided World.* Palgrave Macmillan, Houndmills, Basingstoke, Hampshire, UK and New York, NY, USA, 384 pp.
UNDP, 2009: *Human Development Report 2009: Overcoming Barriers: Human Mobility and Development.* Palgrave Macmillan, Houndmills, Basingstoke, Hampshire, UK and New York, NY, USA, 217 pp.
Unruh, J.D., 2012: The interaction between landmine clearance and land rights in Angola: a volatile outcome of non-integrated peacebuilding. *Habitat International*, **36(1)**, 117-125.
Upton, C., 2012: Managing Mongolia's commons: land reforms, social contexts, and institutional change. *Society & Natural Resources*, **25(2)**, 156-175.
Valdivia, C., A. Seth, J. Gilles, M. García, E. Jiménez, J. Cusicanqui, F. Navia, and E. Yucra, 2010: Adapting to climate change in Andean ecosystems: landscapes, capitals, and perceptions shaping rural livelihood strategies and linking knowledge systems. *Annals of the Association of American Geographers*, **100(4)**, 818-834.
Van de Noort, R., 2011: Conceptualising climate change archaeology. *Antiquity*, **85**, 1039-1048.
van der Geest, K., 2011: North-south migration in Ghana: what role for the environment? *International Migration*, **49(S1)**, 69-94.
Verhoeven, H., 2011: Climate change, conflict and development in Sudan: global Neo-Malthusian narratives and local power struggles. *Development and Change*, **42(3)**, 679-707.
Vermeulen, S. and L. Cotula, 2010: Over the heads of local people: consultation, consent, and recompense in large-scale land deals for biofuels projects in Africa. *Journal of Peasant Studies*, **37(4)**, 899-916.
Villagrán de León, J.C., 2009: Risks in Central America: bringing them under control. In: *Coping with Global Environmental Change, Disasters and Security – Threats, Challenges, Vulnerabilities and Risks* [Brauch, H.G., Ú. Oswald Spring, C. Mesjasz, J. Grin, P. Kameri-Mbote, B. Chourou, P. Dunay, and J. Birkmann (eds.)]. Springer-Verlag Berlin Heidelberg, Germany, pp. 1147-1158.
Vogel, C., S.C. Moser, R.E. Kasperson, and G.D. Dabelko, 2007: Linking vulnerability, adaptation, and resilience science to practice: pathways, players, and partnerships. *Global Environmental Change*, **17(3-4)**, 349-364.
Von Storch, H., G. Gönnert, and M. Meine, 2008: Storm surges – an option for Hamburg, Germany, to mitigate expected future aggravation of risk. *Environmental Science and Policy*, **11(8)**, 735-742.
Vuille, M., B. Francou, P. Wagnon, I. Juen, G. Kaser, B.G. Mark, and R.S. Bradley, 2008: Climate change and tropical Andean glaciers: past, present and future. *Earth Science Reviews*, **89**, 79-96.
Wang, M.Z., M. Amati, and F. Thomalla, 2012: Understanding the vulnerability of migrants in Shanghai to typhoons. *Natural Hazards*, **60(3)**, 1189-1210.
Warner, K., 2010: Global environmental change and migration: governance challenges. *Global Environmental Change*, **20(3)**, 402-413.
Warner, K., 2011: Environmental change and migration: methodological considerations from ground-breaking global survey, *Population and Environment*, **33**, 3-27.
Warner, K., 2012: Human migration and displacement in the context of adaptation to climate change: the Cancun Adaptation Framework and potential for future action. *Environment and Planning C: Government and Policy* **30(6)**, 1061-1077.
Warner, K. and T. Afifi, 2013: Where the rain falls: evidence from 8 countries on how vulnerable households use migration to manage the risk of rainfall variability and food insecurity. *Climate and Development*, doi:10.1080/17565529.2013.835707.
Webersik, C., 2010: *Climate Change and Security: A Gathering Storm of Global Challenges.* Praeger, Santa Barbara, CA, USA, 186 pp.
Weede, E., 2004: On political violence and its avoidance. *Acta Politica*, **39(2)**, 152-178.
Wenzel, G.W., 2009: Canadian Inuit subsistence and ecological instability – if the climate changes, must the Inuit? *Polar Research*, **28(1)**, 89-99.
West, C.T., C. Roncoli, and F. Ouattara, 2008: Local perceptions and regional climate trends on the Central Plateau of Burkina Faso. *Land Degradation and Development*, **19(3)**, 289-304.
West, J.J. and G.K. Hovelsrud, 2010: Cross-scale adaptation challenges in the coastal fisheries: findings from Lebesby, Northern Norway. *Arctic*, **63(3)**, 338-354.
West, J.J., S.J. Smith, R.A. Silva, V. Naik, Y. Zhang, Z. Adelman, M.M. Fry, S. Anenberg, L.W. Horowitz, and J.F. Lamarque, 2013: Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health, *Nature Climatic Change*, **3**, 885-889.
White, G., 2011: *Climate Change and Migration: Security and Borders in a Warming World.* Oxford University Press, Oxford, UK and New York, NY, USA, 180 pp.
White, S., 2011: *The Climate of Rebellion in the Early Modern Ottoman Empire.* Cambridge University Press, New York, NY, USA, 352 pp.
Whyte, K., 2013: Justice forward: tribes, climate adaptation and responsibility. *Climatic Change*, **120(3)**, 517-530, doi:10.1007/s10584-013-0743-2.
Williams, A., 2008: Turning the tide: recognizing climate change refugees in international law. *Law and Policy*, **30(4)**, 502-529.
Williams, J., 2012: The impact of climate change on indigenous people – the implications for the cultural, spiritual, economic and legal rights of indigenous people. *International Journal of Human Rights*, **16(4)**, 648-688.
Wisner, B., 2001: Risk and the neoliberal state: why post-Mitch lessons didn't reduce El Salvador's earthquake losses. *Disasters*, **25(3)**, 251-268.
Wittrock, V., S.N. Kulshreshtha, and E. Wheaton, 2011: Canadian prairie rural communities: their vulnerabilities and adaptive capacities to drought. *Mitigation and Adaptation Strategies for Global Change*, **16(3)**, 267-290.

Wolf, A.T., 2007: Shared waters: conflict and cooperation. *Annual Review of Environment and Resources*, **32**, 241-269.

Wolf, A.T., S.B. Yoffe, and M. Giordano, 2003: International waters: identifying basins at risk. *Water Policy*, **5(1)**, 29-60.

World Bank, 2010: *World Development Report 2010: Development and Climate Change.* The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 417 pp.

Wun'Gaeo, S., 2009: Environment as an element of human security in Southeast Asia: case study on the Thai tsunami. In: *Facing Global Environmental Change: Environmental, Human, Energy, Food, Health and Water Security Concepts* [Brauch, H.G., Ú. Oswald Spring, J. Grin, C. Mesjasz, P. Kameri-Mbote, N.C. Behera, B. Chourou, and H. Krummenacher (eds.)]. Springer-Verlag, Berlin, Heidelberg, Germany, pp. 1131-1142.

Yamamoto, L. and M. Esteban, 2010: Vanishing island states and sovereignty. *Ocean & Coastal Management*, **53(1)**, 1-9.

Young, O.R., 2009: Whither the Arctic? Conflict or cooperation in the circumpolar north. *Polar Record*, **45**, 73-82.

Zamani, G.H., M. Gorgievski-Duijvesteijn, and K. Zarafshani, 2006: Coping with drought: towards a multilevel understanding based on conservation of resources theory. *Human Ecology*, **34(5)**, 677-692.

Zeitoun, M. and J. Warner, 2006: Hydro-hegemony: a framework for analysis of transboundary water conflicts. *Water Policy*, **8(5)**, 435-460.

Zeitoun, M. and N. Mirumachi, 2008: Transboundary water international I: reconsidering conflict and cooperation. *International Environmental Agreements: Politics, Law and Economics*, **8(4)**, 297-316.

Zeitoun, M., T. Allan, N. Al Aulaqi, A. Jabarin, and H. Laamrani, 2012: Water demand management in Yemen and Jordan: addressing power and interests. *Geographical Journal*, **178(1)**, 54-66.

Zhang, D.D., H.F. Lee, C. Wang, B. Li, Q. Pei, J. Zhang, and Y. An, 2011: The causality analysis of climate change and large-scale human crisis. *Proceedings of the National Academy of Sciences of the United States of America*, **108(42)**, 17296-17301.

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Livelihoods and Poverty

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This chapter should be cited as:
Olsson, L., M. Opondo, P. Tschakert, A. Agrawal, S.H. Eriksen, S. Ma, L.N. Perch, and S.A. Zakieldeen, 2014: Livelihoods and poverty. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 793-832.

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Executive Summary

This chapter discusses how livelihoods, poverty and the lives of poor people, and inequality interact with climate change, climate variability, and extreme events in multifaceted and cross-scalar ways. It examines how current impacts of climate change, projected impacts up until 2100, and responses to climate change affect livelihoods and poverty. The Fourth Assessment Report stated that socially and economically disadvantaged and marginalized people are disproportionally affected by climate change. However, no comprehensive review of climate change, poverty, and livelihoods has been undertaken to date by the IPCC. This chapter addresses this gap, presenting evidence of the dynamic interactions between these three principal factors. At the same time, the chapter recognizes that climate change is rarely the only factor that affects livelihood trajectories and poverty dynamics; climate change interacts with a multitude of non-climatic factors, which makes detection and attribution challenging.

Climate-related hazards exacerbate other stressors, often with negative outcomes for livelihoods, especially for people living in poverty (*high confidence*).

- Climate-related hazards, including subtle shifts and trends to extreme events, affect poor people's lives directly through impacts on livelihoods, such as losses in crop yields, destroyed homes, food insecurity, and loss of sense of place, and indirectly through increased food prices (*robust evidence*, *high agreement*). {13.2.1, 13.3}
- Changing climate trends lead to shifts in rural livelihoods with mixed outcomes, such as from crop-based to hybrid livestock-based livelihoods or to wage labor in urban employment. Climate change is one stressor that shapes dynamic and differential livelihood trajectories (*robust evidence*, *high agreement*). {13.1.4, 13.2.1.2}
- Urban and rural transient poor who face multiple deprivations slide into chronic poverty as a result of extreme events, or a series of events, when unable to rebuild their eroded assets. Poverty traps also arise from food price increase, restricted mobility, and discrimination (*limited evidence*, *high agreement*). {13.2.1.3-4}
- Many events that affect poor people are weather-related and remain unrecognized by standard climate observations in many low-income countries, owing to short time series and geographically sparse, aggregated, or partial data, inhibiting detection and attribution. Such events include short periods of extreme temperature, minor changes in the distribution of rainfall, and strong wind events (*robust evidence*, *high agreement*). {13.2.1}

Observed evidence suggests that climate change and climate variability worsen existing poverty, exacerbate inequalities, and trigger both new vulnerabilities and some opportunities for individuals and communities. Poor people are poor for different reasons and thus are not all equally affected, and not all vulnerable people are poor. Climate change interacts with non-climatic stressors and entrenched structural inequalities to shape vulnerabilities (*very high confidence*, based on *robust evidence*, *high agreement*).

- Socially and geographically disadvantaged people exposed to persistent inequalities at the intersection of various dimensions of discrimination based on gender, age, race, class, caste, indigeneity, and (dis)ability are particularly negatively affected by climate change and climate-related hazards. Context-specific conditions of marginalization shape multidimensional vulnerability and differential impacts. {13.1.2.3, 13.1.3., 13.2.1.5}
- Existing gender inequalities are increased or heightened by climate-related hazards. Gendered impacts result from customary and new roles in society, often entailing higher workloads, occupational hazards indoors and outdoors, psychological and emotional distress, and mortality in climate-related disasters. {13.2.1.5}
- There is little evidence that shows positive impacts of climate change on poor people, except isolated cases of social asset accumulation, agricultural diversification, disaster preparedness, and collective action. The more affluent often take advantage of shocks and crises, given their flexible assets and power status. {13.1.4, 13.2.1.4; Figure 13-3}

Climate change will create new poor between now and 2100, in developing and developed countries, and jeopardize sustainable development. The majority of severe impacts are projected for urban areas and some rural regions in sub-Saharan Africa and Southeast Asia (*medium confidence*, based on *medium evidence*, *medium agreement*).

- Future impacts of climate change, extending from the near term to the long term, mostly expecting 2°C scenarios, will slow down economic growth and poverty reduction, further erode food security, and trigger new poverty traps, the latter particularly in urban areas and emerging hotspots of hunger. {13.2.2.2, 13.2.2.4, 13.4}

- Climate change will exacerbate multidimensional poverty in most developing countries, including high mountain states, countries at risk from sea level rise, and countries with indigenous peoples. Climate change will also create new poverty pockets in countries with increasing inequality, in both developed and developing countries. {13.2.2}
- Wage-labor dependent poor households that are net buyers of food will be particularly affected due to food price increases, in urban and rural areas, especially in regions with high food insecurity and high inequality (particularly in Africa), although the agricultural self-employed could benefit {13.2.2.3-4}

Current policy responses for climate change mitigation or adaptation will result in mixed, and in some cases even detrimental, outcomes for poor and marginalized people, despite numerous potential synergies between climate policies and poverty reduction (*medium confidence*, based on *limited evidence*, *high agreement*).

- Mitigation policies with social co-benefits expected in their design, such as Clean Development Mechanism (CDM) and Reduction of Emissions from Deforestation and Forest Degradation (REDD+), have had limited or no effect in terms of poverty alleviation and sustainable development. {13.3.1.1-2}
- Mitigation efforts focused on land acquisition for biofuel production show preliminary negative impacts on the lives of poor people, such as dispossession of farmland and forests, in many developing countries, particularly for indigenous peoples and (women) smallholders. {13.3.1.4}
- Insurance schemes, social protection programs, and disaster risk reduction may enhance long-term livelihood resilience among poor and marginalized people, if policies address multidimensional poverty. {13.3.2.2, 13.4.1}
- Climate-resilient development pathways will have only marginal effects on poverty reduction, unless structural inequalities are addressed and needs for equity among poor and non-poor people are met. {13.4.2}

13.1. Scope, Delineations, and Definitions: Livelihoods, Poverty, and Inequality

Understanding the impacts of climate change on livelihoods and poverty requires examining the complexities of poverty and the lives of poor and non-poor people, as well as the multifaceted and cross-scalar intersections of poverty and livelihoods with climate change. This chapter is devoted to exploring poverty in relation to climate change, a novelty in the IPCC. It uses a livelihood lens to assess the interactions between climate change and multiple dimensions of poverty. We use the term "the poor," not to homogenize, but to describe people living in poverty, people facing multiple deprivations, and the socially and economically disadvantaged, as part of a conceptualization broader than income-based measures of poverty, acknowledging gradients of prosperity and poverty. This livelihood lens also reveals how inequalities perpetuate poverty to shape differential vulnerabilities and in turn the differentiated impacts of climate change on individuals and societies. The chapter first presents the concepts of livelihoods, poverty, and inequality, and their relationships to each other and to climate change. Second, it describes observed impacts of weather events and climate on livelihoods and rural and urban poor people as well as projected impacts up to 2100. We use "weather events and climate" as an umbrella term for climate change, climate variability, and extreme events, and also highlight subtle shifts in precipitation and localized weather events. Third, this chapter discusses impacts of climate change mitigation and adaptation responses on livelihoods and poverty. Finally, it outlines implications for poverty alleviation efforts and climate-resilient development pathways.

Livelihoods and Poverty is a new chapter in the AR5. Although the WGII AR4 contributions mentioned poverty, as one of several non-climatic factors contributing to vulnerability, as a serious obstacle to effective adaptation, and in the context of endemic poverty in Africa (Chapters 7, 8, 18, 20), no systematic assessment was undertaken. Livelihoods were more frequently addressed in the AR4 and in the *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX), predominantly with reference to livelihood strategies and opportunities, diversification, resource-dependent communities, and sustainability. Yet, a comprehensive livelihood lens for assessing impacts was lacking. This chapter addresses these gaps. It assesses how climate change intersects with other stressors to shape livelihood choices and trajectories, to affect the spatial and temporal dimensions of poverty dynamics, and to reduce or exacerbate inequalities given differential vulnerabilities.

13.1.1. Livelihoods

Livelihoods (see also Glossary) are understood as the ensemble or opportunity set of capabilities, assets, and activities that are required to make a living (Chambers and Conway, 1992; Ellis et al., 2003). They depend on access to natural, human, physical, financial, social, and cultural capital (assets); the social relations people draw on to combine, transform, and expand their assets; and the ways people deploy and enhance their capabilities to act and make lives meaningful (Scoones, 1998; Bebbington, 1999). Livelihoods are dynamic and people adapt and change their livelihoods with internal and external stressors. Ultimately, successful livelihoods transform assets into income, dignity, and agency, to improve living conditions, a prerequisite for poverty alleviation (Sen, 1981).

Livelihoods are universal. Poor and rich people both pursue livelihoods to make a living. However, as shown in this chapter, the adverse impacts of weather events and climate increasingly threaten and erode basic needs, capabilities, and rights, particularly among poor and disenfranchised people, in turn reshaping their livelihoods (UNDP, 2007; Leary et al., 2008; Adger, 2010; Quinn et al., 2011). Some livelihoods are directly climate sensitive, such as rainfed smallholder agriculture, seasonal employment in agriculture (e.g., tea, coffee, sugar), fishing, pastoralism, and tourism. Climate change also affects households dependent on informal livelihoods or wage labor in poor urban settlements, directly through unsafe settlement structures or indirectly through rises in food prices or migration.

13.1.1.1. Dynamic Livelihoods and Trajectories

A livelihood lens is a grounded and multidimensional perspective that recognizes the flexibility and constraints with which people construct their complex lives and adapt their livelihoods in dynamic ways. By paying attention to the wider institutional, cultural, and policy contexts as well as shocks, seasonality, and trends, this lens reveals processes that push people onto undesirable trajectories or toward enhanced well-being. Better infrastructure and technology as well as diversification of assets, activities, and social support capabilities can boost livelihoods, spreading risks and broadening opportunities (Batterbury, 2001; Ellis et al., 2003; Clot and Carter, 2009; Carr, 2013; Reed et al., 2013). The sustainable livelihoods framework (Chambers and Conway, 1992) is widely used for identifying how specific strategies may lead to cycles of livelihood improvements or critical thresholds beyond which certain livelihoods are no longer sustainable (Sabates-Wheeler et al., 2008). It emerged as a reaction to the predominantly structural views of poverty and "underdevelopment" in the 1970s and became adopted by many researchers and development agencies (Ellis and Biggs, 2001). With the neoliberal turn in the late 1980s, the livelihoods approach became associated with a more individualistic development agenda, stressing various forms of capital (Scoones, 2009). Consequently, it has been criticized for its analytical limitations, such as measuring capitals or assets, especially social capital, and for not sufficiently explaining wider structural processes (e.g., policies) and ecological impacts of livelihood decisions (Small, 2007; Scoones, 2009). An overemphasis on capitals also eclipses power dynamics and the position of households in class, race, and other dimensions of inequality (Van Dijk, 2011).

13.1.1.2. Multiple Stressors

Livelihoods rarely face only one stressor or shock at a time. The literature emphasizes the synergistic relationship between weather events and climate and a variety of other environmental, social, economic, and political stressors; together, they impinge on livelihoods and reinforce each other in the process, often negatively (Reid and Vogel, 2006; Schipper and Pelling, 2006; Easterling et al., 2007; IPCC, 2007; Morton, 2007; Tschakert, 2007; O'Brien et al., 2008; Eriksen and Silva, 2009; Eakin and Wehbe, 2009; Ziervogel et al., 2010). "Double losers" may

Frequently Asked Questions

FAQ 13.1 | What are multiple stressors and how do they intersect with inequalities to influence livelihood trajectories?

Multiple stressors are simultaneous or subsequent conditions or events that provoke/require changes in livelihoods. Stressors include climatic (e.g., shifts in seasons), socioeconomic (e.g., market volatility), and environmental (e.g., destruction of forest) factors, that interact and reinforce each other across space and time to affect livelihood opportunities and decision making (see Figure 13-1). Stressors that originate at the macro level include climate change, globalization, and technological change. At the regional, national, and local levels, institutional context and policies shape possibilities and pitfalls for lessening the effects of these stressors. Which specific stressors ultimately result in shocks for particular livelihoods and households is often mediated by institutions that connect the local level to higher levels. Moreover, inequalities in low-, medium-, and high-income countries often amplify the effects of these stressors. This is particularly the case for livelihoods and households that have limited asset flexibility and/or those that experience disadvantages and marginalization due to gender, age, class, race, (dis)ability, or being part of a particular indigenous or ethnic group. Weather events and climate compound these stressors, allowing some to benefit and enhance their well-being while others experience severe shocks and may slide into chronic poverty. Who is affected, how, where, and for how long depends on local contexts. For example, in the Humla district in Nepal, gender roles and caste relations influence livelihood trajectories in the face of multiple stressors including shifts in the monsoon season (climatic), limited road linkages (socioeconomic), and high elevation (environmental). Women from low castes have adapted their livelihoods by seeking more day-labor employment, whereas men from low castes ventured into trading on the Nepal-China border, previously an exclusively upper caste livelihood.

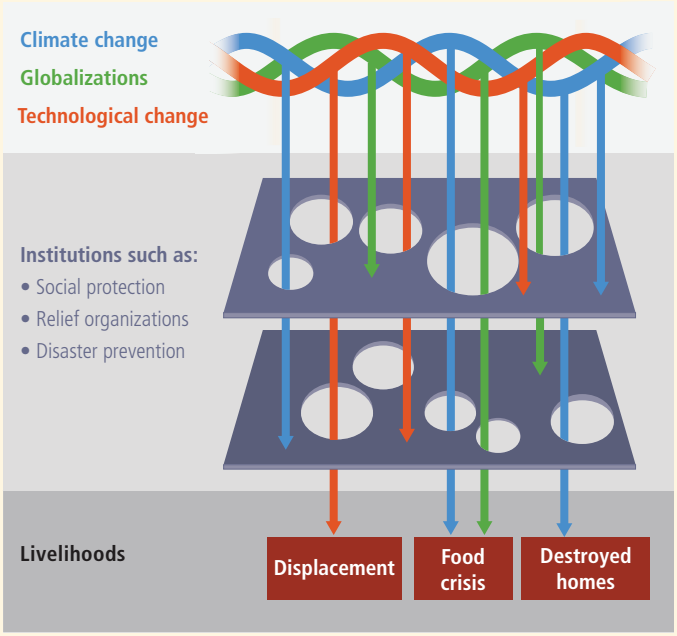


Figure 13-1 | Multiple stressors related to climate change, globalizations, and technological change interact with national and regional institutions to create shocks to place-based livelihoods, inspired by Reason (2000).

emerge from simultaneous exposure to climatic change and other stressors such as the spread of infectious diseases, rapid urbanization, and economic globalization, where climate change acts as a threat multiplier, further marginalizing vulnerable groups (O'Brien and Leichenko, 2000; Eriksen and Silva, 2009). Climatic and other stressors affect livelihoods at different scales: spatial (e.g., village, nation) or temporal (e.g., annual, multi-annual). Both direct and indirect impacts are often amplified or weakened at different levels. Global or regional processes generate a variety of stressors, typically mediated by cross-level institutions, that result in locally experienced shocks (Reid and Vogel, 2006; Thomas et al., 2007; Paavola, 2008; Pouliotte et al., 2009; see also Figure 13-1 in FAQ 13.1).

Multiple stressors, simultaneous and in sequence, shape livelihood dynamics in distinct ways due to inequalities and differential vulnerabilities between and within households. More affluent households may be able to capitalize on shocks and crises while poorer households with fewer options are forced to erode their assets. Limited ability to adapt and some coping strategies may result in adverse consequences. Such maladaptive actions (see Glossary, and Chapters 14, 16) undermine the long-term sustainability of livelihoods, resulting in downward trajectories, poverty traps, and exacerbated inequalities (Ziervogel et al., 2006; Tanner and Mitchell, 2008; Barnett and O'Neill, 2010).

13.1.2. Dimensions of Poverty

Poverty is a complex concept with conflicting definitions and considerable disagreement in terms of framings, methodologies, and measurements. Despite different approaches emphasizing distinct aspects of poverty at the individual or collective level—such as income, capabilities, and quality of life (Laderchi et al., 2003)—poverty is recognized as multidimensional (UNDP, 1990). It is influenced by social, economic, institutional, political, and cultural drivers; its reversal requires efforts

in multiple domains that promote opportunities and empowerment, and enhance security (World Bank, 2001). In addition to material deprivation, multidimensional conceptions of poverty consider a sense of belonging and socio-cultural heritage (O'Brien and Leichenko, 2003), identity, and agency, or "the culturally constrained capacity to act" (Ahearn, 2001, p. 54). The AR4 identified poverty as "the most serious obstacle to effective adaptation" (Confalonieri et al., 2007, p. 417).

13.1.2.1. Framing and Measuring Multidimensional Poverty

Over the last 6 decades, conceptualizations of poverty have broadened, expanding the basis for understanding poverty and its drivers. Poverty measurements now better capture multidimensional characteristics and spatial and temporal nuances. Attention to multidimensional deprivations—such as hunger; illiteracy; unclean drinking water; lack of access to health, credit, or legal services; social exclusion; and disempowerment—have shifted the analytical lens to the dynamics of poverty and its institutionalization within social and political norms (UNDP, 1994; Sen, 1999; World Bank, 2001). Regardless of these shifting conceptualizations over time, comparable and reliable measures remain challenging and income per capita remains the default method to account for the depth of global poverty.

In climate change literature, poverty and poverty reduction have been predominantly defined through an economic lens, reflecting various growth and development discourses (Sachs, 2006; Collier, 2007). Less attention has been paid to relational poverty, produced through material social relations and in relation to privilege and wealth (Sen, 1976; Mosse, 2010; Alkire and Foster, 2011; UNDP, 2011a). Yet, such framing allows for addressing the social and political contexts that generate and perpetuate poverty and structural vulnerability to climate change (McCright and Dunlap, 2000; Bandiera et al., 2005; Leichenko and O'Brien, 2008). Many climate policies to date favor market-based responses using sector-specific and economic growth models of development, although some responses may slow down achievements of international development such as those outlined in the Millennium Development Goals (MDGs). For instance, the World Bank encourages "mitigation, adaptation, and the deployment of technologies" that "allow[s] developing countries to continue their growth and reduce poverty" (World Bank, 2010, p. 257), mainly promoted through market tools. A relational approach to poverty highlights the integral role of poor people in all social relations (Pogge, 2009; O'Brien et al., 2010; UNRISD, 2010; Gasper et al., 2013; St.Clair and Lawson, 2013). It emphasizes equity, human security, and dignity (O'Connor, 2002; Mosse, 2010). Akin to the capabilities approach (Sen, 1985, 1999; Nussbaum, 2001, 2011; Alkire, 2005), the relational approach stresses the needs, skills, and aims of poor people while tackling structural causes of poverty, inequalities, and uneven power relations.

The IPCC AR4 (Yohe et al., 2007) highlighted that—with *very high confidence*—climate change will impede the ability of nations to alleviate poverty and achieve sustainable development, as measured by progress toward the MDGs. Empirical assessments of the impact of

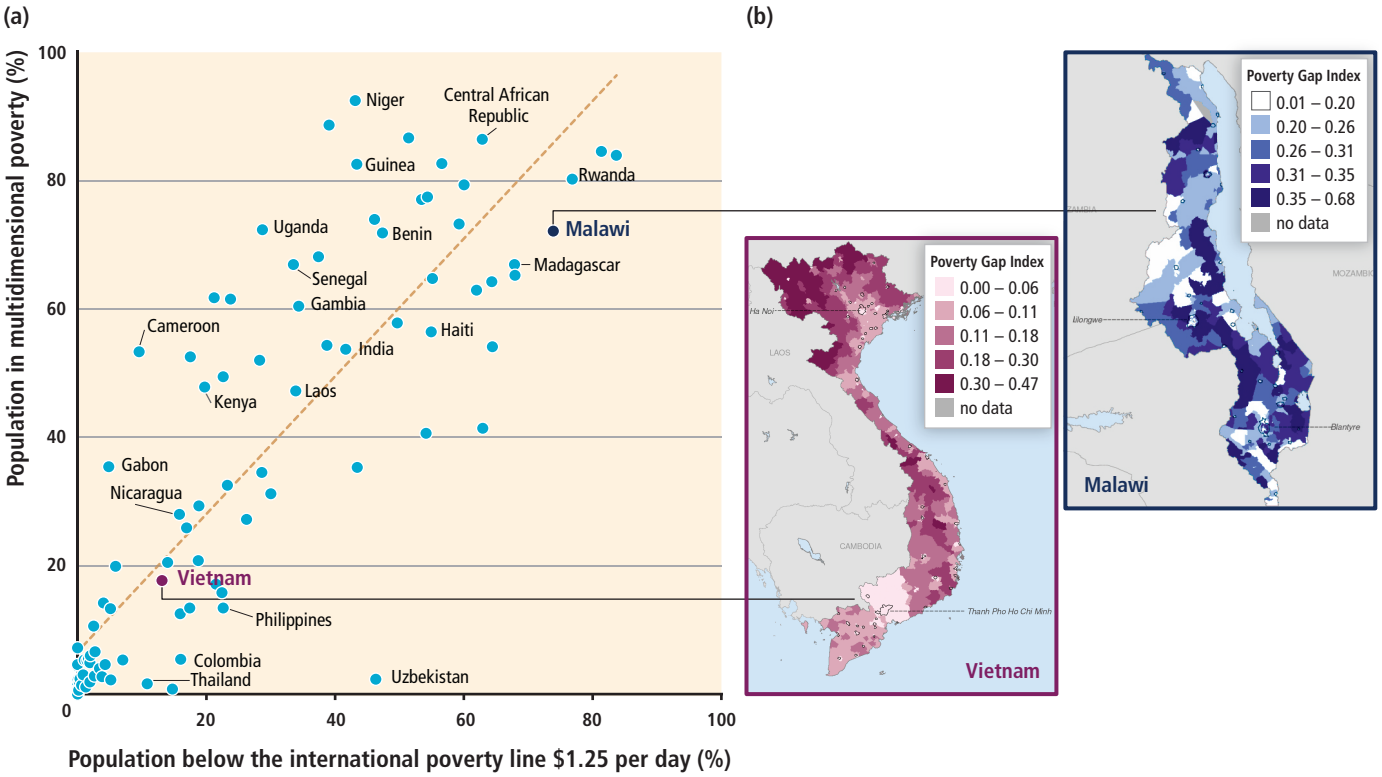


Figure 13-2 | (a) Multidimensional poverty and income-based poverty using the International Poverty Line $1.25 per day (in Purchasing Power Parity terms), with linear regression relationship (dotted line) based on 96 countries (UNDP, 2011b). The position of the countries relative to the dotted line illustrates the extent to which these two poverty measures are similar or divergent. (b) The map insets show the intensity of poverty in two countries, based on the Poverty Gap Index at district level (per capita measure of the shortfall in welfare of the poor from the poverty line, expressed as a ratio of the poverty line): the darker the shading, the larger the shortfall.

climate change on MDG attainment are limited (Fankhauser and Schmidt-Traub, 2011), and the failure to reach these goals by 2015 has significant non-climatic causes (e.g., Hellmuth et al., 2007; UNDP, 2007). The 2010 UNDP Multidimensional Poverty Index, measuring intensity of poverty based on patterns of simultaneous deprivations in basic services (education, health, and standard of living) and core human functionings, states that close to 1.7 billion people face multidimensional poverty, a significantly higher number than the 1.2 billion (World Bank, 2012a) indicated by the International Poverty Line (IPL) set at $1.25 per day. Figure 13-2 depicts country-level examples of how the two poverty measures differ.

Caution is required for poverty projections. Estimates of poverty made using national accounts means (see Chapter 19) yield drastically different estimates to those produced by survey means, both for current estimates and future projections (Edward and Sumner, 2013a). Diverse conceptions of poverty further complicate projections, as multidimensional conceptions rely on concepts difficult to measure and compare. Data availability constrains current estimates let alone projections and their core assumptions (Alkire and Santos, 2010; Karver et al., 2012).

13.1.2.2. Geographic Distribution and Trends of the World's Poor

Geographic patterns of poverty are uneven and shifting. Despite its limitations, most comparisons to date rely on the IPL. In the remainder of the text, we use the World Bank income-based poverty categories for countries (low-income countries, lower-middle-income countries, upper-middle-income countries, and high-income countries); these categories are more precise and more accurate for describing climate change impacts on poverty than the terminology adopted in the Summary for Policymakers and the respective chapter Executive Summaries (i.e., 'developing' and 'developed' countries). Moreover, much of the assessed literature is based on these categories. In 1990, most of the world's $1.25 and $2 poor lived in low-income countries (LICs). By 2008, the majority of the poor living on $1.25 and $2 (>70%) resided in lower- and upper-middle-income countries (LMICs and UMICs), in part because some populous LICs such as India, Nigeria, and Pakistan grew in per capita income to MIC status (Sumner, 2010, 2012a). Estimates suggest about 1 billion people currently living on less than $1.25 per day in MICs and a second billion between $1.25 and $2, with an additional 320 million and 170 million in LICs, respectively (Sumner, 2012b). About 70% of the poor subsisting on $1.25 per day live in rural areas in the global South (IFAD, 2011), despite worldwide urbanization. Yet, this poverty line understates urban poverty as it does not fully account for the higher costs of food and non-food items in many urban contexts (Mitlin and Satterthwaite, 2013). Of the approximately 2.4 billion living on less than $2 per day, half live in India and China. At the same time, relative poverty is rising in HICs. Many European countries face rapid increases in poverty, unemployment, and the number of working poor due to recent austerity measures. For example, 20% of Spanish citizens were ranked poor in 2009 (Ortiz and Cummins, 2013). See also Chapter 23.

The shift in distribution of global poverty toward MICs and the increase in relative poverty in HICs challenge the orthodox view that most of the world's poorest people live in the poorest countries, and suggests that substantial pockets of poverty persist in countries with higher levels of average per capita income. Understanding this shift in the geography of poverty and available social safety nets is vital for assessing climate change impacts on poverty. To date, both climate finance and research on climate impacts and vulnerabilities are directed largely toward LICs. Less attention has been paid to poor people in MICs and HICs. In the upper and lower MICs, the incidence of $2 per day poverty, despite declines, remains as high as 60% and 20%, respectively (Sumner, 2012b).

Projections for 2030 suggest $2 per day poverty as high as 963 million people in sub-Saharan Africa and 851 million in India (Sumner et al., 2012; Edward and Sumner, 2013a). However, uncertainty is high in terms of future growth and inequality trends; by 2030, $1.25 and $2 per day global poverty could be reduced to 300 million and 600 million respectively or remain at or above current levels, including in stable MICs (Edward and Sumner, 2013a). These future scenarios become more uncertain if climate change impacts on people who are socially and economically disadvantaged are taken into account or diversion of resources from poverty reduction and social protection to mitigation strategies is considered.

13.1.2.3. Spatial and Temporal Scales of Poverty

Poverty is also socially distributed, across spatial and temporal scales. Not everybody is poor in the same way. Spatially, factors such as access to and control over resources and institutional linkages from individuals to the international level affect poverty distribution (Anderson and Broch-Due, 2000; Murray, 2002; O'Laughlin, 2002; Rodima-Taylor, 2011). Even at the household level, poverty differs between men and women and age groups, yet data constraints impede systematic intra-household analysis (Alkire and Santos, 2010). The distribution of poverty also varies temporally, typically between chronic and transient poverty (Sen, 1981, 1999). Chronic poverty describes an individual deprivation, per capita income, or consumption levels below the poverty line over many years (Gaiha and Deolalikar, 1993; Jalan and Ravallion, 2000; Hulme and Shepherd, 2003). Transient poverty denotes a temporary state of deprivation, and is frequently seasonal and triggered by an individual's or household's inability to maintain income or consumption levels in times of shocks or crises (Jalan and Ravallion, 1998).

Individuals and households can fluctuate between different degrees of poverty and shift in and out of deprivation, vulnerability, and well-being (Leach et al., 1999; Little et al., 2008; Sallu et al., 2010). Yet, the most disadvantaged often find themselves in poverty traps, or situations in which escaping poverty becomes impossible without external assistance due to unproductive or inflexible asset portfolios (Barrett and McPeak, 2006). A poverty trap can also be seen as a "critical minimum asset threshold, below which families are unable to successfully educate their children, build up their productive assets, and move ahead economically over time" (Carter et al., 2007 p. 837). As of 2008, a total of 320 to 443 million of people were trapped in chronic poverty (Chronic Poverty Research Centre, 2008), leading Sachs (2006) to label less than $1.25 per day poverty as a trap in itself. Poverty traps at the national level are often related to poor governance, reduced foreign investment, and conflict (see Chapters 10, 12).

13.1.3. Inequality and Marginalization

Specific livelihoods and poverty alone do not necessarily make people vulnerable to weather events and climate. The socially and economically disadvantaged and the marginalized are disproportionately affected by the impacts of climate change and extreme events (*robust evidence*; Kates, 2000; Paavola and Adger, 2006; Adger et al., 2007; Cordona et al., 2012). The AR4 identified poor and indigenous peoples in North America (Field et al., 2007) and in Africa (Boko et al., 2007) as highly vulnerable. Vulnerability, or the propensity or predisposition to be adversely affected (IPCC, 2012a) by climatic risks and other stressors (see also Glossary), emerges from the intersection of different inequalities, and uneven power structures, and hence is socially differentiated (Sen, 1999; Banik, 2009; IPCC, 2012a). Vulnerability is often high among indigenous peoples, women, children, the elderly, and disabled people who experience multiple deprivations that inhibit them from managing daily risks and shocks (Eriksen and O'Brien, 2007; Ayers and Huq, 2009; Boyd and Juhola, 2009; Barnett and O'Neill, 2010; O'Brien et al., 2010; Petheram et al., 2010) and may present significant barriers to adaptation.

Global income inequality has been relatively consistent since the late 1980s. In 2007, the top quintile of the world's population received 83% of the total income whereas the bottom quintile took in 1% (Ortiz and Cummins, 2011). Since 2005, between-country inequality has been falling more quickly and, consequently, has triggered a notable decline in total global inequality in the last few years (Edward and Sumner, 2013b). However, within-country inequality is rising in Asia, especially China, albeit from relatively low levels, and is falling in Latin America, albeit from very high levels, while trends in sub-Saharan Africa are difficult to discern regionally (Ravallion and Chen, 2012). Income inequality is rising in many fast growing LICs and MICs (Dollar et al., 2013; Edward and Sumner, 2013b). It is also growing in many HICs owing to a combination of factors such as changing tax systems, privatization of social services, labor market regulations, and technological change (OECD, 2011). The 2008 financial crisis, combined with climate change, has further threatened economic growth in HICs, such as the UK, and resources available for social policies and welfare systems (Gough, 2010). Recognizing how inequality and marginalization perpetuate poverty is a prerequisite for climate-resilient development pathways (see Section 13.4; Chapters 1, 20, 27).

13.1.4. Interactions between Livelihoods, Poverty, Inequality, and Climate Change

This chapter opens its analytical lens from a conventional focus on the poor in LICs as the prime victims of climate change to a broader understanding of livelihood and poverty dynamics and inequalities, revealing the highly unequal impacts of climate change. It highlights the complex relationship between climate change and poverty. The SREX recognizes that addressing structural inequalities that create and sustain poverty and vulnerability (Huq et al., 2005; Schipper, 2007; Lemos et al., 2007; Boyd and Juhola, 2009; Williams, 2010; Perch, 2011) is a crucial precondition for confronting climate change (IPCC, 2012a). If ignored, uneven social relations that disproportionally burden poor people with climate change's negative impacts provoke maladaptation (Barnett and O'Neill, 2010).

Poverty and persistent inequality are the "most salient of the conditions that shape climate-related vulnerability" (Ribot, 2010, p. 50). They affect livelihood options and trajectories, and create conditions in which people have few assets to liquidate in times of hardship or crisis (Mearns and Norton, 2010). People who are poor and marginalized usually have the least buffer to face even modest climate hazards and suffer most from successive events with little time for recovery. They are the first to experience asset erosion, poverty traps, and barriers and limits to adaptation. As shown in Sections 13.2 and 13.3, climate change is an additional burden to people in poverty (*very high confidence*), and it

Frequently Asked Questions

FAQ 13.2 | How important are climate change-driven impacts on poverty compared to other drivers of poverty?

Climate change-driven impacts are one of many important causes of poverty. They often act as a threat multiplier, meaning that the impacts of climate change compound other drivers of poverty. Poverty is a complex social and political problem, intertwined with processes of socioeconomic, cultural, institutional, and political marginalization, inequality, and deprivation, in low-, middle-, and even high-income countries. Climate change intersects with many causes and aspects of poverty to worsen not only income poverty but also undermine well-being, agency, and a sense of belonging. This complexity makes detecting and measuring attribution to climate change exceedingly difficult. Even modest changes in seasonality of rainfall, temperature, and wind patterns can push transient poor and marginalized people into chronic poverty as they lack access to credit, climate forecasts, insurance, government support, and effective response options, such as diversifying their assets. Such shifts have been observed among climate-sensitive livelihoods in high mountain environments, drylands, and the Arctic, and in informal settlements and urban slums. Extreme events, such as floods, droughts, and heat waves, especially when occurring in a series, can significantly erode poor people's assets and further undermine their livelihoods in terms of labor productivity, housing, infrastructure, and social networks. Indirect impacts, such as increases in food prices due to climate-related disasters and/or policies, can also harm both rural and urban poor people who are net buyers of food.

will force poor people from transient into chronic poverty and create new poor (*medium confidence*).

The complex interactions among weather events and climate, dynamic livelihoods, multidimensional poverty and deprivation, and persistent inequalities, including gender inequalities, create an ever-shifting context of risk. The SREX concluded that climate change, climate variability, and extreme events synergistically add on to and often reinforce other environmental, social, and political calamities (IPCC, 2012a). Despite the recognition of these complex interactions, the literature shows no single conceptual framework that captures them concurrently, and few studies exist that overlay gradual climatic shifts or rapid-onset events onto livelihood risks. Hence, explicit attention to how livelihood dynamics interact with climatic and non-climatic stressors is useful for identifying processes that push poor and vulnerable people onto undesirable trajectories, trap them in destitution, or facilitate pathways toward enhanced well-being. Figure 13-3 illustrates these dynamics as well as critical thresholds in livelihood trajectories.

13.2. Assessment of Climate Change Impacts on Livelihoods and Poverty

This section reviews the evidence and agreement about the relationships among climate change, livelihoods, poverty, and inequality. Building on deductive reasoning and theorized linkages about these dynamic relationships, this section draws on a wide range of empirical case studies and simulations to illustrate linkages across multiple scales, contexts, and social and environmental processes and to assess impacts of climate change. Although cases of observed impacts often rely on qualitative data and at times lack methodological clarity in terms of detection and attribution, they provide a vital evidence base for conveying these complex relationships. This section first describes observed impacts to date (Section 13.2.1) and then projected risks and impacts (Section 13.2.2).

13.2.1. Evidence of Observed Climate Change Impacts on Livelihoods and Poverty

Weather events and climate affect the lives and livelihoods of millions of poor people (IPCC, 2012b). Even minor changes in precipitation amount or temporal distribution, short periods of extreme temperatures, or localized strong winds can harm livelihoods (Douglas et al., 2008; Ostfeld, 2009; Midgley and Thuiller, 2011; Bele et al., 2013; Bryan et al., 2013). Many such events remain unrecognized given that standard climate observations typically report precipitation or temperature by month, season, or year, thus obscuring changes that shape decision making, for instance, in agriculture (Tennant and Hewitson, 2002; Barron et al., 2003; Usman and Reason, 2004; Douglas et al., 2008; Lacombe et al., 2012; Salack et al., 2012). This difficulty in detection and attribution is compounded by a lack of long-term continuous and dense networks of climate data in many LICs (UNECA, 2011). Felt experiences of events such as drought, as shown among the Sumbanese in Eastern Indonesia through phenomenological research on perceptions of climatic phenomena, such as shade and dew (Orr et al., 2012), further add to the complexity.

13.2.1.1. Impacts on Livelihood Assets and Human Capabilities

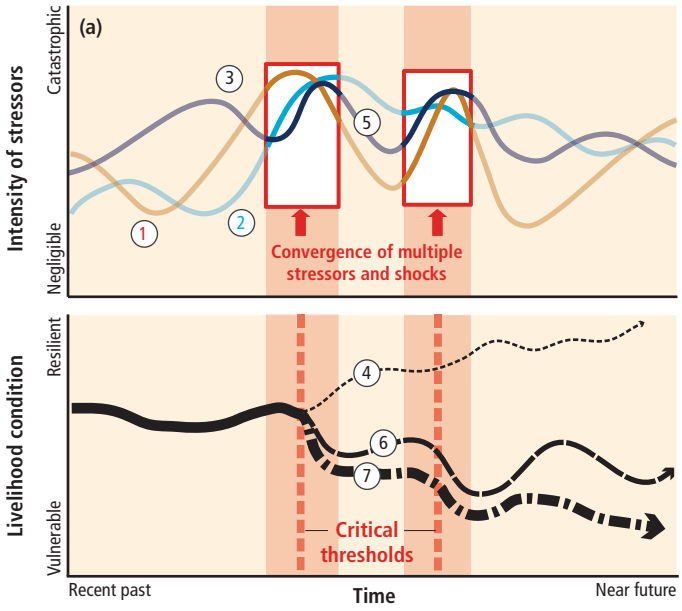
Climate change, climate variability, and extreme events interact with numerous aspects of people's livelihoods. This section presents empirical evidence of impacts on natural, physical, financial, human, and social and cultural assets (see also Chapters 22 to 29). Impacts on access to assets, albeit important, are poorly documented in the literature, as are impacts on power relations and active struggles in designing effective and relational livelihood arrangements.

Weather events and climate affect *natural assets* on which certain livelihoods depend directly, such as rivers, lakes, and fish stocks (*robust evidence*; Thomas et al., 2007; Nelson and Stathers, 2009; Osbahr et al., 2010; Bunce et al., 2010a,b; D'Agostino and Sovacool, 2011; see also Chapters 3, 4, 5, 6, 30). During the 20th century, water temperatures increased and winds decreased in Lake Tanganyika (Adrian et al., 2009; Verburg and Hecky, 2009; Tierney et al., 2010). Since the late 1970s, a drop in primary production and fish catches, a key protein source, has been observed, and climate change may exceed the effects of overfishing and other human impacts in this area (O'Reilly et al., 2003). The Middle East and North Africa (MENA) face dwindling water resources due to less precipitation and rising temperatures combined with mounting water demand due to population and economic growth (Tekken and Kropp, 2012), resulting in rapidly decreasing water availability that, in 2025, could be 30 to 70% less per person (Sowers et al., 2011). In MENA (Sowers et al., 2011), the Andes and Himalayas (Orlove, 2009), the Caribbean (Cashman et al., 2010), Australia (Alston, 2011), and in cities (Satterthwaite, 2011), policy allocation often favors more affluent consumers, at the expense of less powerful rural and/or poor users.

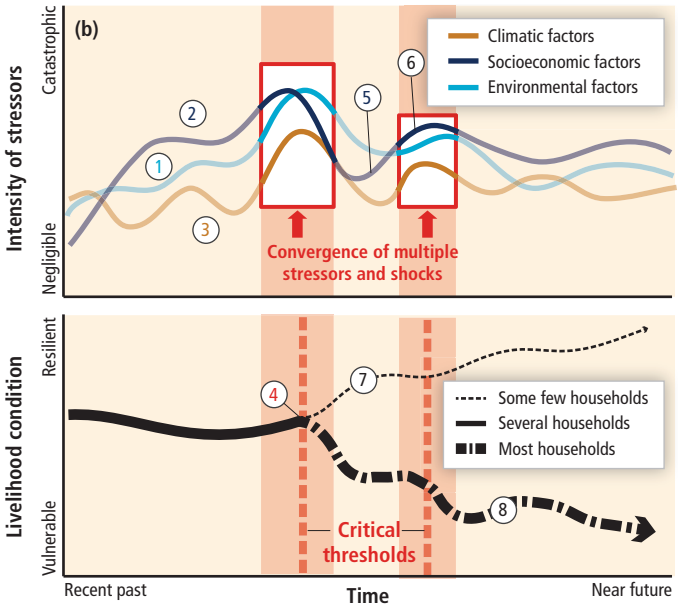
Weather events and climate also erode farming livelihoods (see Chapters 7, 9), via declining crop yields (Hassan and Nhemachena, 2008; Apata et al., 2009; Sissoko et al., 2011; Sietz et al., 2012; Li et al., 2013), at times compounded by increased pathogens, insect attacks, and parasitic weeds (Stringer et al., 2007; Byg and Salick, 2009), and less availability of and access to non-timber forest products (Hertel and Rosch, 2010; Nkem et al., 2012) and medicinal plants and biodiversity (Van Noordwijk, 2010). For agropastoral and mixed crop-livestock livelihoods, extreme high temperatures threaten cattle (Hahn, 1997; Thornton et al., 2007; Mader, 2012; Nesamvuni et al., 2012); in Kenya, for instance, people may shift from dairy to beef cattle and from sheep to goats (Kabubo-Mariara, 2008).

The most extreme form of erosion of natural assets is the complete disappearance of people's land on islands and in coastal regions (McGranahan et al., 2007; Solomon et al., 2009), exacerbating livelihood risks due to loss of economic and social assets (see Chapters 5, 29; Perch and Roy, 2010). Densely populated coastal cities with high poverty such as Alexandria and Port Said in Egypt (El-Raey et al., 1999), Cotonou in Benin (Dossou and Glehouenou-Dossou, 2007), and Lagos and Port Harcourt in Nigeria (Abam et al., 2000; Fashae and Onafeso, 2011) are already affected by floods and at risk of submersion. Resettlements are planned for the Limpopo River and the Mekong River Delta (de Sherbinin et al., 2011) and small island states may become uninhabitable (Burkett, 2011).

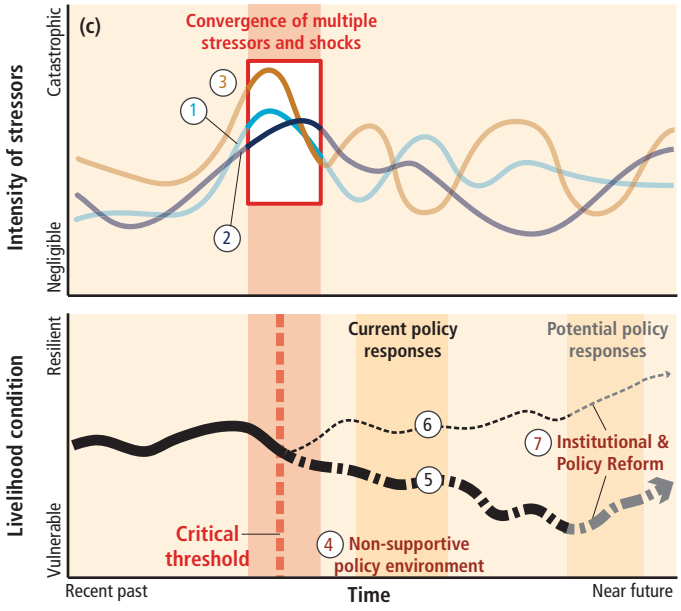
Damage to *physical assets* due to weather events and climate is well documented for poor urban settlements, often built in risk-prone



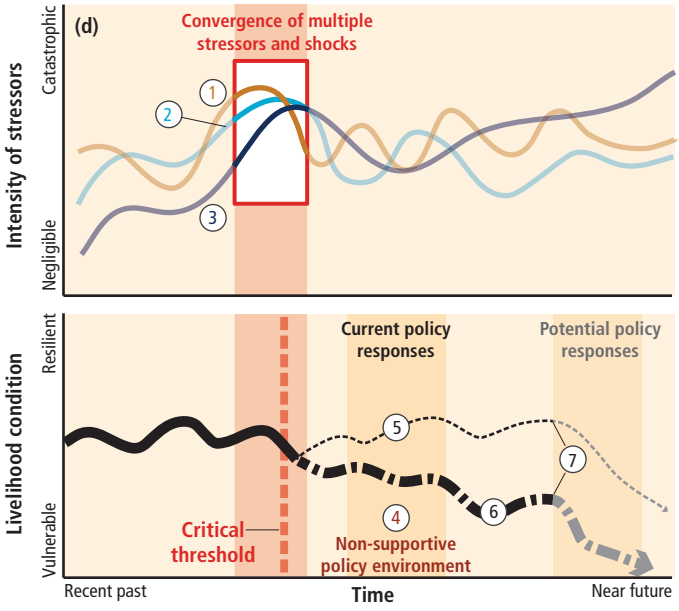
(a) Botswana's drylands (Sallu et al., 2010). Over the past 30 years, rural households have faced droughts, late onset and increased unpredictability of rainfall, and frost (1), drying of Lake Xau, and land degradation (2). Households responded differently to these stressors, given their financial and physical assets, diversification of and within livelihood activities, family relations, and institutional and governmental support. Despite weakening of social networks and declining livestock due to lack of water (3), distinct livelihood trajectories emerged. "Accumulators" were often able to benefit from crises, for instance through access to salaried employment (4) or new hunting quotas (5), while "dependent" households showed a degenerative trajectory, losing more and more livelihood assets, and becoming reliant on governmental support after another period of convergent stressors (6). "Diversifiers" had trajectories fluctuating between vulnerable and resilient states (7).



(b) Coastal Bangladesh (Pouliotte et al., 2010). In the Sunderbans, a combination of environmental and socioeconomic factors, out of which climatic stressors appear to play only a minor role, have changed livelihoods: saltwater intrusion (1) due to the construction and poor management of the Bangladeshi Coastal Embankment Project, the construction of a dam in India, local water diversions (2), and sea level rise and storm surges (3). The convergence of these stressors caused households to cross a critical threshold from rice and vegetable cultivation to saltwater shrimp farming (4). A strong export market and international donor and national government support facilitated this shift (5). However, increasing density of shrimp farming then triggered rising disease levels (6). Wealth and power started to become more concentrated among a few affluent families (7) while livelihood options for the poorer households further diminished due to lacking resources to grow crops in salinated water, the loss of grazing areas and dung from formerly accessible rice fields (8), and rising disease levels (6).



(c) Mountain environments (McDowell and Hess, 2012). Indigenous Aymara farmers in highland Bolivia face land scarcity, pervasive poverty, climate change, and lack of infrastructure due in part to racism and institutional marginalization. The retreat of the Mururata glacier causes water shortages (1), compounded by the increased water requirements of cash crops on smaller and smaller "minifundios" and market uncertainties (2). High temperatures amplify evaporation, and flash floods coupled with delayed rainfall cause irrigation canals to collapse (3). The current policy environment makes it difficult to access loans and obtain land titles (4), pushing many farmers onto downward livelihood trajectories (5) while those who can afford it invest in fruit and vegetable trees at higher altitudes (6). Sustained access to land, technical assistance, and irrigation infrastructure would be effective policy responses to enhance well-being (7).



(d) Urban flooding in Lagos (Adelekan, 2010). Flooding threatens the livelihoods of people in Lagos, Nigeria, where >70 % live in slums. Increased severity in rainstorms, sea level rise, and storm surges (1) coupled with the destruction of mangroves and wetlands (2), disturb people's jobs as traders, wharf workers, and artisans, while destroying physical and human assets. Urban management, infrastructure for water supply, and stormwater drainage have not kept up with urban growth (3). Inadequate policy responses, including uncontrolled land reclamation, make these communities highly vulnerable to flooding (4). Only some residents can afford sand and broken sandcrete blocks (5). Livelihood conditions in these slums are expected to further erode for most households (6). Given policy priorities for the construction of high-income residential areas, current residents fear eviction (7).

Figure 13-3 | Illustrative representation of four case studies that describe livelihood dynamics under simultaneous climatic, environmental, and socioeconomic stressors, shocks, and policy responses – leading to differential livelihood trajectories over time. The red boxes indicate specific critical moments when stressors converge, threatening livelihoods and well-being. Key variables and impacts numbered in the illustrations correspond to the developments described in the captions.

floodplains and hillsides susceptible to erosion and landslides. Impacts include homes destroyed by flood water and disrupted water and sanitation services. Flooding has adversely affected large cities in Africa (Douglas et al., 2008) and Latin America (Hardoy and Pandiella, 2009; Hardoy et al., 2011), in predominantly dense informal settlements due to inadequate drainage, and health infrastructure (UNDP, 2011c). Yet, upper-middle- and high-income households living in flood-prone areas or high-risk slopes frequently can afford insurance and lobby for protective policies, in contrast to poor residents (Hardoy and Pandiella, 2009). Loss of physical assets in poor areas after disasters is often followed by displacement due to loss of property (Douglas et al., 2008). Increasing flash floods attributed to climate change (Sudmeier-Rieux et al., 2012) have severely damaged terraces, orchards, roads, and stream embankments in the Himalayas (Azhar-Hewitt and Hewitt, 2012; Hewitt and Mehta, 2012).

Erosion of *financial assets* as a result of climatic stressors include losses of farm income and jobs (Hassan and Nhemachena, 2008; Iwasaki et al., 2009; Alderman, 2010; Jabeen et al., 2010; Alston, 2011) and increased costs of living such as higher expenses for funerals (Gabrielsson et al., 2012). In South and Central America, more than 600 weather and extreme events occurred 2000–2013, resulting in 13,500 fatalities, 52.6 million people affected, and economic losses of US$45.3 billion (www.emdat.be). Income losses due to weather events mean less money for agricultural inputs (seeds, equipment), school tuition, uniforms, and books, and health expenses throughout the year (Thomas et al., 2007). Flooding in informal settlements in Lagos undermines job opportunities (Adelekan, 2010).

Equally important, albeit frequently overlooked, is the damage to human assets as a result of weather events and climate, such as food insecurity, undernourishment, and chronic hunger due to failed crops (*medium evidence*) (Patz et al., 2005; Funk et al., 2008; Zambian Government, 2011; Gentle and Maraseni, 2012) or spikes in food prices most severely felt among poor urban populations (Ahmed et al., 2009; Hertel and Rosch, 2010). During the Ethiopian drought (1998–2000) and Hurricane Mitch in Nicaragua (1998), poorer households tended to engage in asset smoothing, reducing their consumption to very low levels to protect their assets, whereas wealthier households sold assets and smoothed consumption (Carter et al., 2007). In such cases, poor people further erode nutritional levels and human health while holding on to their limited assets. Dehydration, heat stroke, and heat exhaustion from exposure to heat waves undermine people's ability to carry out physical work outdoors and indoors (Semenza et al., 1999; Kakota et al., 2011). Psychological effects from extreme events include sleeplessness, anxiety and depression (Byg and Salick, 2009; Keshavarz et al., 2013), loss of sense of place and belonging (Tschakert et al., 2011; Willox et al., 2012), and suicide (Caldwell et al., 2004; Alston, 2011) (see also Chapter 11 and Box CC-HS).

Finally, weather events and climate also erode *social and cultural assets*. In some contexts, climatic and non-climatic stressors and changing trends disrupt informal social networks of the poorest, elderly, women, and women-headed households, preventing mobilization of labor and reciprocal gifts (Osbahr et al., 2008; Buechler, 2009) as well as formal social networks, including social assistance programs (Douglas et al., 2008). Indigenous peoples (see Chapter 12) witness their cultural points of reference disappearing (Ford, 2009; Bell et al., 2010; Green et al., 2010).

13.2.1.2. Impacts on Livelihood Dynamics and Trajectories

Weather events and climate also affect livelihood trajectories and dynamics in livelihood decision making, often in conjunction with cross-scalar socioeconomic, institutional, or political stressors. Shifting in and out of hardship and well-being on a seasonal basis is not uncommon. To a large extent, the shifts from coping and hardship to recovery are driven by annual and interannual climate variability, but may become exacerbated by climate change. Figure 13-4 illustrates seasonal livelihood sensitivity for the Lake Victoria Basin in East Africa (Gabrielsson et al., 2012).

Shifts in livelihoods often occur due to changing climate trends, linked to a series of environmental, socioeconomic, and political stressors (*robust evidence*). Farmers may change their crop choices instead of abandoning farming (Kurukulasuriya and Mendelsohn, 2007) or take on more lucrative income-generating activities (see Figure 13-3). Uncertainty about West Africa's rainy season threatens small-scale farming and water management (Yengoh et al., 2010a,b; Armah et al., 2011; Karambiri et al., 2011; Lacombe et al., 2012). Around Mali's drying Lake Faguibine, livelihoods shifted from water-based to agro-sylvo-pastoral systems, as a direct impact of lower rainfall and more frequent and more severe droughts (Brockhaus and Djoudi, 2008). Diverse indigenous groups in Russia have changed their livelihoods as result of Soviet legacy and climate change; for example, many Viliui Sakha have abandoned cow-keeping due to youth out-migration, growing access to consumer goods, and seasonal changes in temperature, rainfall, and snow (Crate, 2013). Under certain converging shocks and stressors, people adopt entirely new livelihoods. In South Africa, higher precipitation uncertainty raised reliance on livestock and poultry rather than crops alone in 80% of households interviewed (Thomas et al., 2007). In southern Africa and India, people migrated to the coasts, switching from climate-sensitive farming to marine livelihoods (Coulthard, 2008; Bunce et al., 2010a,b). After Hurricane Stan (2005), land-poor coffee farmers in Chiapas, Mexico, turned from specializing in coffee to being day laborers and subsistence farmers (Eakin et al., 2012).

13.2.1.3. Impacts on Poverty Dynamics: Transient and Chronic Poverty

Limited evidence documents the extent to which climate change intersects with poverty dynamics, yet there is *high agreement* that shifts from transient to chronic poverty due to weather and climate are occurring, especially after a series of weather or extreme events (Scott-Joseph, 2010). Households in transient poverty may become chronically poor due to a lack of effective response options to weather events and climate, compared with more affluent households (see Figure 13-3). Often, multiple deprivations drive these shifts, with socially and economically marginalized groups particularly prone to slipping into chronic poverty. Women-headed households, children, people in informal settlements (see Chapter 8), and indigenous communities are particularly at risk, owing to compounding stressors such as lack of governmental

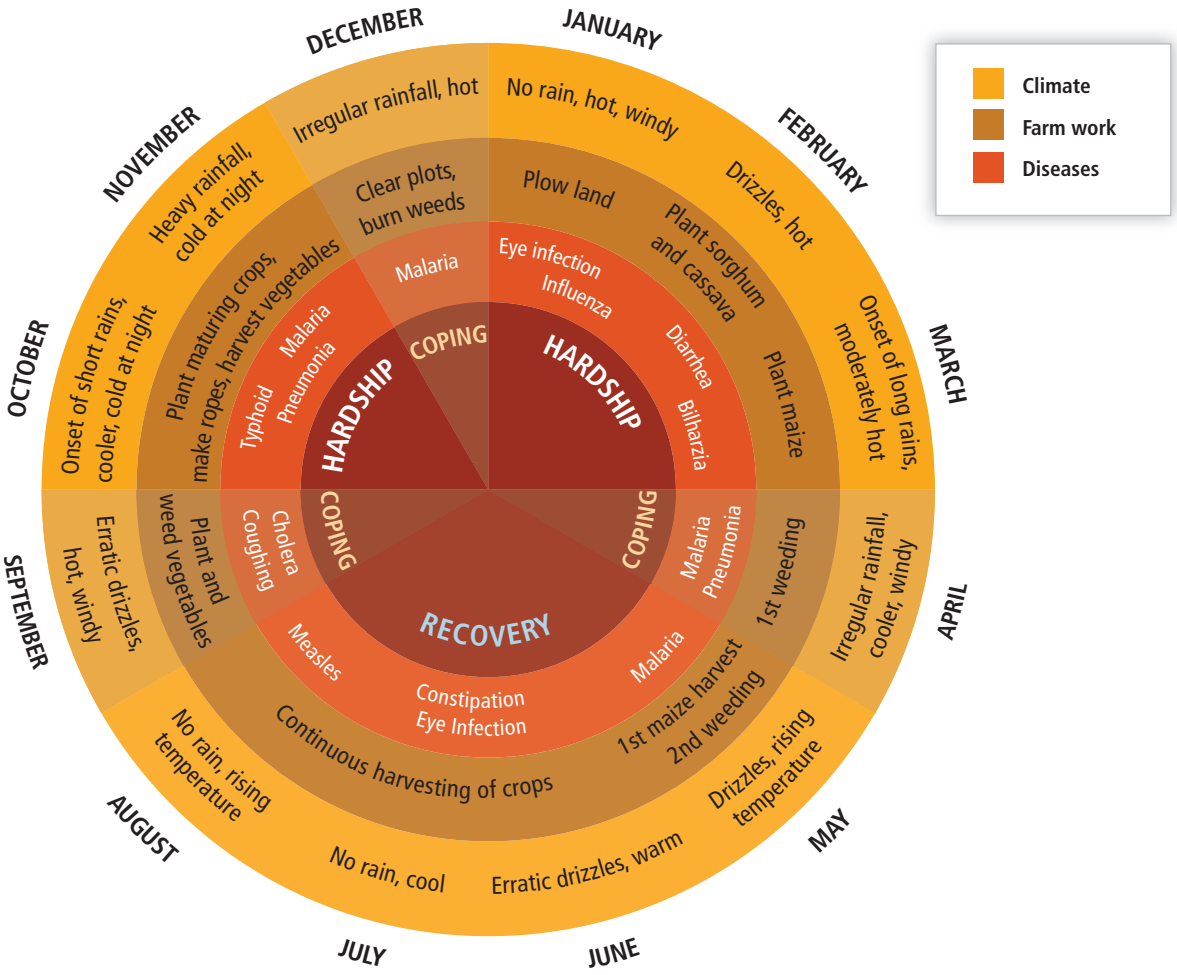


Figure 13-4 | Seasonal sensitivity of livelihoods to climatic and non-climatic stressors for one calendar year, based on experiences of smallholder farmers in the Lake Victoria Basin in Kenya and Tanzania (Gabrielsson et al., 2012).

support, urban infrastructure, and insecure land tenure (see Section 13.2.1.5 and Chapter 12).

Poor people in urban areas in LICs and MICs in Africa, Asia, and Latin America may slip from transient to chronic poverty given the combination of population growth and flooding threats in low-elevation cities and water stress in drylands (Balk et al., 2009) along with other multiple deprivations (Mitlin and Satterthwaite, 2013). Poverty shifts also occur in response to food price increases, though the strength of the relationship between weather events and climate and food prices is still debated (see Chapter 7 and Section 13.3.1.4). Poor households in urban and rural areas are particularly at risk when they are almost exclusively net buyers of food (Cranfield et al., 2007; Cudjoe et al., 2010; Ruel et al., 2010). Misselhorn (2005) showed in a meta-study of 49 cases of food insecurity in southern Africa that climatic drivers and poverty were the two dominant and interacting causal factors. Poor pastoralists have collapsed into chronic poverty when livestock assets have been lost (Thornton et al., 2007). In rural areas, restricted forest access may exacerbate poverty among already income-poor and elderly households who rely on forest resources to respond to climatic shocks (Fisher et al., 2010). Yet, many such shifts remain underexplored, incompletely captured in poverty data and adaptation monitoring. The bulk of evidence in the literature is oriented toward extreme events, rapid-onset disasters, and subsequent impacts on livelihoods and poor people's lives. Subtle changes are rarely tracked, making quantification of long-term trends and detection of impacts difficult.

13.2.1.4. Poverty Traps and Critical Thresholds

Poverty traps arise when climate change, variability, and extreme events keep poor people poor and make some poor even poorer. Yet, attribution remains a challenge. Among disadvantaged people in urban areas, poverty traps are reported especially for wage laborers who erode their financial capital due to increases in food prices (Ahmed et al., 2009; Hertel and Rosch, 2010) and for those in informal settlements exposed to floods and landslides (Hardoy and Pandiella, 2009). In rural areas, poverty traps are reported when climate change impacts on poor people persist over decades, such as through environmental degradation and recurring stress on ecosystems in the Sahel (Kates, 2000; Hertel and Rosch, 2010; Sissoko et al., 2011; UNCCD, 2011), or when people are unable to rebuild assets after a series of stresses (Eriksen and O'Brien, 2007; Sabates-Wheeler et al., 2008; Sallu et al., 2010). Poverty traps and destitution are also described in pastoralist systems, triggered through droughts, restricted mobility owing to conflict and insecurity, adverse terms of trade, and the conversion of grazing areas to agricultural land,

such as for biofuel production (Eriksen and Lind, 2009; Homewood, 2009; Eriksen and Marin, 2011). Other poverty traps result from heavy debt loads due to the inability to repay loans and distress sales (Renton, 2009; Ahmed et al., 2012), persistent discrimination through legal structures and formal institutions, especially for women and other marginalized groups (Campbell et al., 2009; McDowell and Hess, 2012), and at the nexus of climate, health, and conflict (see Chapter 10).

Despite *limited evidence*, there is *high agreement* that critical thresholds, or irreversible damage (Heltberg et al., 2009), result from the convergence of various factors, many of which are not directly related to climate change. For instance, poor people often rely on social networks, including reciprocal gifts and exchanges, to protect themselves from shocks and crises such as droughts and illness (Little et al., 2006). Yet, given limited assets and ability to mobilize labor and food, particularly for smaller and women-headed households and the elderly, the exhaustion of these reciprocal ties can indicate an imminent slipping into poverty traps or chronic poverty (Pradhan et al., 2007; Osbahr et al., 2008). Injuries, disabilities, disease, psychological distress, for example from accidents during flood events, diminish poor people's main asset, labor (Douglas et al., 2008), and may plunge them into chronic poverty.

Few studies illustrate positive livelihood impacts as a result of climate change or climate-induced shocks, and they often tend to refer to more affluent and powerful constituencies. Very scarce evidence exists of poor people escaping poverty traps (see Figure 13-3). In Cameroon, though, farming communities benefit from occasional rainfall during the dry season and more food stuffs while the drying of swamps allows maize off season (Bele et al., 2013). In Lake Victoria Basin, collective action has increased as a result of HIV/AIDS and climate change, boosting social assets (Gabrielsson and Ramasar, 2012). Lessons from Hurricane Mitch (1998) in Honduras point toward more equitable land distribution and better flood preparedness that benefit the poor after disasters (McSweeney and Coomes, 2011).

13.2.1.5. Multidimensional Inequality and Vulnerability

Climate variability and change as well as climate-related disasters contribute to and exacerbate inequality, in urban and rural areas, in LICs, MICs, and HICs. Mounting inequality is not just a side effect of weather and climate but of the interaction of related impacts with multiple deprivations at the context-specific intersections of gender, age, race, class, caste, indigeneity, and (dis)ability, embedded in uneven power structures, also known as intersectionality (Nightingale, 2011; Kaijser and Kronsell, 2013; see Figure 13-5). This section illustrates how climate impacts intersect with inequality, primarily along the lines of gender, age, and indigeneity. Other chapters are referenced.

Medium evidence highlights impacts of climate stresses and extreme events on *children* (Cutter et al., 2012; O'Brien et al., 2012). Children in urban slums suffer from inadequate water supplies and malnutrition, which

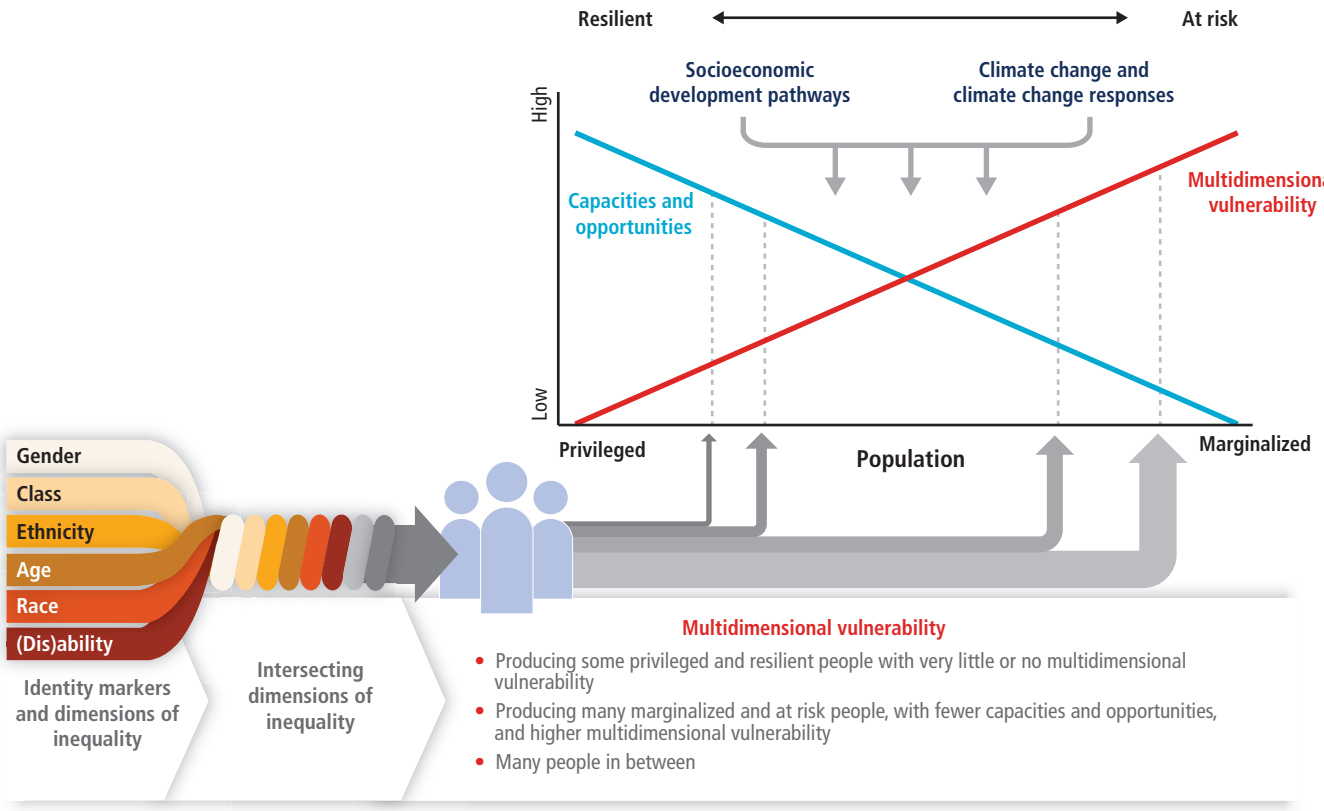


Figure 13-5 | Multidimensional vulnerability driven by intersecting dimensions of inequality, socioeconomic development pathways, and climate change and climate change responses. Vulnerability depends on the structures in society that trigger or perpetuate inequality and marginalization—not just income-poverty, location, or one dimension of inequality in itself, such as gender.

exacerbates impacts from heat stress, while excessive rain heightens water-borne diseases (Bartlett, 2008). Flood-related mortality in Nepal was twice as high for girls as for women (13.3 per 1000 girls) and also higher for boys than for men, and for young children in general six times higher than before the flood (Pradhan et al., 2007). Lower caloric intake due to two back-to-back droughts and price shocks in Zimbabwe in the 1980s resulted in physical stunting among children and reduced lifetime earnings (Alderman, 2010). In Mali, the incidence of child food poverty increased from 41% to 52% since the 2006 food price increases (Bibi et al., 2010). See Chapter 11 for more details.

Health impacts of weather events and climate differentially affect *the elderly* and *socially isolated* (Frumkin et al., 2008; see also Chapter 11). In Vietnam the elderly, widows, and disabled people, in addition to

Box 13-1 | Climate and Gender Inequality: Complex and Intersecting Power Relations

Existing ***gender inequality*** (see Box CC-GC) is increased or heightened as a result of weather events and climate-related disasters intertwined with socioeconomic, institutional, cultural, and political drivers that perpetuate differential vulnerabilities (*robust evidence*; Lambrou and Paina, 2006; Adger et al., 2007; Brouwer et al., 2007; Shackleton et al., 2007; Carr, 2008; Demetriades and Esplen, 2008; Galaz et al., 2008; Osbahr et al., 2008; Buechler, 2009; Nightingale, 2009; Terry, 2009; Dankelman, 2010; MacGregor, 2010; Alston, 2011; Arora-Jonsson, 2011; Resurreccion, 2011; Heckenberg and Johnston, 2012; Zotti et al., 2012; Alston and Whittenbury, 2013; Rahman, 2013; Shah et al., 2013). While earlier studies have tended to highlight women's quasi-universal vulnerability in the context of climate change (e.g., Denton, 2002), this focus can ignore the complex, dynamic, and intersecting power relations and other structural and place-based causes of inequality (Nightingale, 2009; UNFPA, 2009; Arora-Jonsson, 2011). Moreover, the construction of economically poor women as victims denies women's agency and emphasizes their vulnerability as their intrinsic problem (MacGregor, 2010; Manzo, 2010; Arora-Jonsson, 2011).

Gendered livelihood impacts: Men and women are differentially affected by climate variability and change. The 10-year drought in Australia's Murray-Darling Basin differentially affected men and women, owing to their distinct roles within agriculture (e.g., Eriksen et al., 2010). Alston (2011) noted social disruption and depression, most profound in areas with almost total reliance on agriculture, no substitute employment, and limited service infrastructure (Table 13-1). In India, more women than men, especially women of lower castes, work as wage laborers to compensate for crop losses (Lambrou and Nelson, 2013) while in Tanzania, wealthier women hire poorer women to collect animal fodder during droughts (Muthoni and Wangui, 2013). Climate variability amplifies food shortages in which women consume less food (Lambrou and Nelson, 2013) and suffer from reproductive tract infections and water-borne diseases after floods (Neelormi et al., 2008; Campbell et al., 2009). Women farmers in the Philippines relying on high-interest loans were sent to jail after defaulting on debts following crop failure (Peralta, 2008). In Uganda, men were able to amass land after floods while droughts reduced women's non-land assets (Quisumbing et al., 2011). In Ghana, some husbands prevent their wives from cultivating individual plots as a response to gradually shifting rainfall seasonality, thereby undermining both women's agency and household well-being (Carr, 2008).

Table 13-1 | Examples of gendered climate experiences.

Experiences	Male farmers	Female farmers
Increased workload	Demanding tasks such as feeding livestock, carting water, destroying frail animals (A)	Assistance with farm tasks and working off the farm for additional income (A)
	Increased migration for wage labor, typically farther away from home (I)	Increased collection of firewood and uptake of wage labor (especially lower castes) in neighboring villages (I)
Community interactions, isolation, and exploitation	Locked into farms, loss of political power (A)	Increased interactions and caregiving work, taking care of others' health at the expense of their own (A)
	Exploitation by labor contractors when migrating (I)	Disadvantage in accessing institutional support and climate information (I)
Physical and psychological toll	Feel demonized (farmers seen as responsible for crisis), increased stress, social isolation, depression, and high suicide levels (A)	Working lives appear indefinite, resulting in increased stress (A)
	Increased anxiety to provide food and access loans and escape trap of indebtedness, increase in domestic fights, sometimes suicide (I)	Increased pressure to provide food and save some more from sale for consumption, less food intake, increase in domestic fights (I)

(A) = Australia (ten-year drought, 2003–2012), based on Alston (2011); (I) = India (climate variability and changing climatic trends), based on Lambrou and Nelson (2013).

Continued next page →

Box 13-1 (continued)

Feminization of responsibilities: Campbell et al. (2009) and Resurreccion (2011), in case studies from Vietnam, found increased workloads for both partners linked to weather events and climate, contingent on socially accepted gender roles: men tended to work longer hours during extreme events and women adopted extra responsibilities during disaster preparation and recovery (e.g., storing food and water and taking care of the children, the sick, and the elderly) and when their husbands migrated. In Cambodia, Khmer men and women accepted culturally taboo income-generating activities under duress, when rice cropping patterns shifted due to higher temperatures and more irregular rainfall (Resurreccion, 2011). Despite increased workloads for both sexes, women's extra work adds to already many labor and caring duties (Nelson and Stathers, 2009; MacGregor, 2010; Petrie, 2010; Arora-Jonsson, 2011; Kakota et al., 2011; Resurreccion, 2011; Muthoni and Wangui, 2013; Shah et al., 2013). In Nepal, shifts in the monsoon season, longer dry periods, and decreased snowfall push Dalit girls and women ("untouchable" caste) to grow drought-resistant buckwheat and offer more day labor to the high caste Lama landlords while Dalit men seek previously taboo patronage protection to engage in cross-border trade (Onta and Resurreccion, 2011). Rising male out-migration, for example, in Niger and South Africa, leave women with all agricultural tasks yet limited extra labor (Goh, 2012). Additional workloads exhaust women emotionally and physically, shown in South Africa (Babugura, 2010).

Occupational hazards: Increasing cases of heat death are reported among male workers on sugarcane plantations in El Salvador due to kidney failure (Peraza et al., 2012) and heat-related indoor work emergencies in Spain among young (<50 years) able-bodied urban men (García-Pina et al., 2008). Anecdotal evidence suggests that women tea pickers in Malawi, Kenya, India, and Sri Lanka suffer and die from heat stress as payment by quantity discourages rest breaks (Renton, 2009; see also Chapter 11 and CC-HS). In cases of male out-migration due to unsustainable rural livelihoods, women in Bangladesh face unsafe working conditions, exploitation, and loss of respect (Pouliotte et al., 2009). Yet, male out-migration could provide opportunities for women to move beyond traditionally constrained roles, explore new livelihood options, and access public decision-making space (CIDA, 2002; Fordham et al., 2011).

Emotional and psychological distress: Climate-related disasters or gradual environmental deterioration can affect women's mental health disproportionally due to their multiple social roles (UN ECLAC, 2005; Babugura, 2010; Boetto and McKinnon, 2013; Hargreaves, 2013). Increased gender-based violence within households is reported as an indirect social consequence of climate-related disasters, as well as slow-onset climate events, owing to greater stress and tension, loss and grief, and disrupted safety nets, reported for Australia (Anderson, 2009; Alston, 2011; Parkinson et al., 2011; Hazeleger, 2013; Whittenbury, 2013), New Zealand (Houghton, 2009), the USA (Jenkins and Phillips, 2008; Anastario et al., 2009), Vietnam (Campbell et al., 2009), and Bangladesh (Pouliotte et al., 2009).

Mortality: Social conditioning affects mortality for women and men. Rahman (2013) and Nellemann et al. (2011) confirm patterns of gender disparity with respect to swimming that contribute to high number of female deaths due to climate-related disasters. Restricted mobility keeps women in Bangladesh and Nicaragua waiting in risk-prone houses during floods (Saito, 2009; Bradshaw, 2010). Some disaster relief structures that lack facilities appropriate for women may contribute to increased harm and mortality (World Bank, 2010). When they are socioeconomically disadvantaged and the disasters exacerbate existing patterns of discrimination, more women die in hurricanes and floods (Neumayer and Plümper, 2007; Ray-Bennett, 2009). Yet, men experience a higher mortality rate when fulfilling culturally imposed roles as heroic life-savers (Röhr, 2006; Campbell et al., 2009; Resurreccion, 2011).

single mothers and women-headed households with small children, were least resilient to floods and storms and slow-onset events such as recurrent droughts (Campbell et al., 2009). In Australia, older citizens have shown feelings of distress as a result of familiar landscapes altered by drought, loss of home gardens, social isolation, and physical harm related to heat stress and wild fires (Pereira and Pereira, 2008; Horton et al., 2010; Polain et al., 2011). Elderly citizens in the UK may underestimate the risk and severity of heat waves through their social networks and fail to act (Wolf et al., 2010). In the USA, Europe, and South Korea, the elderly, children, and persons of lower socioeconomic status have a heightened risk of heat-related mortality (Baccini et al., 2008; Balbus and Malina, 2009; Son et al., 2012). Preliminary evidence suggests

differential harm of 2012 Superstorm Sandy in New York, observed among elderly people and medically underserved populations (Pagán Motta, 2013; Teperman, 2013; Uppal et al., 2013).

Inequality and disproportionate effects of climate-related impacts also occur along the axes of *indigeneity and race*. Disproportionate climate impacts are documented for Afro-Latinos and displaced indigenous groups in urban Latin America (Hardoy and Pandiella, 2009), and indigenous peoples in the Russian North (Crate, 2013) and the Andes (Andersen and Verner, 2009; Valdivia et al., 2010; McDowell and Hess, 2012; Sietz et al., 2012). See Chapter 12 for impacts on indigenous cultures. In the USA, low-income people of color are more affected by climate-related disasters (Sherman and Shapiro, 2005; Morello-Frosch et al., 2009; Lynn et al., 2011) as demonstrated in the case of low-income African American residents of New Orleans after Hurricane Katrina (Elliott and Pais, 2006).

13.2.2. Understanding Future Impacts of and Risks from Climate Change on Livelihoods and Poverty

Future climate change, as projected through modeling, will continue to affect poor people in rural and urban areas in LICs, MICs, and HICs, alter their livelihoods, and make efforts to reduce poverty more difficult (*high confidence*). Studies reveal a broad range of impacts for the near- (2030–2040) and long-term (2080–2100) future, depending on the climatic, agro-economic, and demographic models employed, their key variables, and spatial scale, which vary from a country's agro-ecological zones to the global. Few projections take into account policy options or adaptation.

Projections emphasize the complexity and heterogeneity of future climate impacts, including winners and losers in close geographic proximity. Anticipated impacts on the poor are expected to interact with multiple stressors, most notably social vulnerability (Iglesias et al., 2011), low adaptive capacity and subsistence constraints under chronic poverty (Liu et al., 2008), weak institutional support (Menon, 2009; Xu et al., 2009; Skoufias et al., 2011a,b), population increases (Müller et al., 2011), natural resource dependence (Adano et al., 2012), ethnic conflict and political instability (Challinor et al., 2007; Adano et al., 2012), large-scale land conversions (Assuncao and Cheres, 2008; Thornton et al., 2008), and inequitable trade relations (Challinor et al., 2007; Jacoby et al., 2011).

Table 13-2 illustrates estimated risks and adaptation potentials for livelihoods and poverty dimensions until 2100.

13.2.2.1. Projected Risks and Impacts by Geographic Region

Climate change will exacerbate risks and in turn further entrench poverty (*very high confidence*). The well-known and highly referenced Wheeler data set (2011) analyzes climate risk and coping ability by country. Future increases in the frequency of extreme events are overlaid with considerable poverty, although not all poor people will be at risk. Of the 20 countries and regions most at risk, seven are LICs (Bangladesh, Ethiopia, Kenya, Madagascar, Mozambique, Somalia, and Zimbabwe), eight are LMICs (Bolivia, Djibouti, Honduras, India, Philippines, Sri Lanka, Vietnam, and Zambia), four are UMICs (China, Colombia, Cuba, and Thailand), and one is an HIC (Hong Kong). For China, Djibouti, India, Kenya, and Somalia, climate contributes between 46.4% and 87.5% to a 2008–2015 rise in national risk, compared to income and urbanization. Highest sensitivity to sea level rise by 2050, based on low-elevation coastal zones, population density, and areas of storm surge zones, is expected for India, Indonesia, China, the Philippines, and Bangladesh. India and Indonesia are projected to experience a 80% and 60% increase, respectively, in their populations at risk from sea level rise, housing a combined total of more than 58 million people most at risk by 2050; 6 million people more at risk from sea level rise in China will bring its total to 22 million, and Bangladesh's at-risk population is predicted to grow to 27 million—more than double since 2008 (Wheeler, 2011).

Specific regions at high risk are those exposed to sea level rise and extreme events and with concentrated multidimensional poverty, including pockets of poor people in LICs and MICs: mega-deltas in Bangladesh, Thailand, Myanmar, and Vietnam (Eastham et al., 2008; Wassmann et al., 2009), drylands (Anderson et al., 2009; Piao et al., 2010; Sietz et al., 2011), mountain areas (Beniston, 2003; Valdivia et al., 2010; Gentle and Maraseni, 2012; Gerlitz et al., 2012; McDowell and Hess, 2012), watersheds in the Himalayas (Xu et al., 2009), ecologically fragile areas in China (Taylor and Xiaoyun, 2012), coastal areas with severe ecosystem deterioration in eastern and southern Africa (Bunce et al., 2010a,b), and river deltas subject to resource extraction (Syvitski et al., 2009).

13.2.2.2. Anticipated Impacts on Economic Growth and Agricultural Productivity

Most projected future impact studies focus on the long-term effects of climatic changes and shocks on agricultural productivity, mainly in Africa, Asia, and Latin America. They typically examine impacts on economic growth (see also Chapter 10), changes in food prices and food security, and extrapolated changes in poverty head counts.

For future poverty head counts caused by climate change, the literature shows disagreement. For the very near future, a study by Thurlow et al. (2009) estimates that, by 2016, Zambia's poverty headcount would increase by 300,000 people under average climate variability, and by 650,000 under a worst 10-year rainfall sequence. Skoufias et al. (2011b), using 2055 predictions based on the Nordhaus (2010) RICE (Regional dynamic Integrated model of Climate and the Economy) model, state that under business-as-usual and optimal abatement, global poverty (measured at $2 per day) could be reduced by 800 million people, owing to annual and real per capita growth rate of 2.2% up to 2055. However, lower probability extreme events would reverse this trend, and mitigation under optimal abatement typically excludes people living in poverty (Skoufias et al., 2011b).

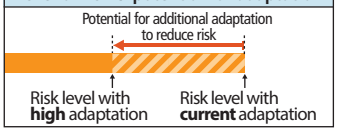
In contrast, Tubiello et al. (2008) project that, by 2080, the number of undernourished people may increase by up to 170 million, using the A2 *Special Report on Emission Scenarios* (SRES) scenarios, and up to a total of 1300 million people assuming no carbon dioxide (CO_2) fertilization.

Table 13-2 | Key risks from climate change for poor people and their livelihoods and the potential for risk reduction through adaptation. Key risks are identified based on assessment of the literature and expert judgment by chapter authors, with evaluation of evidence and agreement in the supporting chapter sections. Each key risk is characterized as very low, low, medium, high, or very high. Risk levels are presented in three timeframes: present, near-term (2030–2040), and long term (2080–2100). Near term indicates that projected levels of global mean temperature do not diverge substantially across emissions scenarios. Long term differentiates between a global mean temperature increase of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adaptive state. Bars that only show the latter indicate a limit to adaptation (see Chapter 16). Relevant climate variables are indicated by symbols. This table should not be used as a basis for ranking severity of risks.

Climate-related drivers of impacts



Level of risk & potential for adaptation



Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Deteriorating livelihoods in drylands, due to high and persistent poverty. Risk of reaching tipping points for crop and livestock production in small-scale farming and/or pastoralist livelihoods (*high confidence*) [13.2.1.2, 13.2.2.1, 13.2.2.3]	Adaptation options are limited owing to persistent poverty, declining land productivity, food insecurity, and limited government support due to marginalization. Rural–urban migration is a potential adaptation strategy.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	Very low / Medium / Very high
Destruction and deterioration of assets: physical (homes, land, and infrastructure), human (health), social (social networks), cultural (sense of belonging and identity), and financial (savings) due to floods in flood-prone areas, such as low-lying deltas, coasts, and small islands (*high confidence*) [13.2.1.1, 13.2.1.3, 13.2.1.5, Box 13-1]	Adaptation options are limited for people who cannot afford relocation to safer areas. Government support and private options (e.g., insurance) are limited for people with insecure or unclear tenure.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	Very low / Medium / Very high
Shifts from transient to chronic poverty due to persistent economic and political marginalization of poor people combined with deteriorating food security (*high confidence*) [13.2.1.3, 13.2.2.4]	Adaptation options are limited due to exclusion from markets and low government support. Policies for adaptation are unsuccessful because of failure to address persistent inequalities.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	Very low / Medium / Very high
Declining work productivity, morbidity (e.g., dehydration, heat stroke, and heat exhaustion), and mortality from exposure to heat waves. Particularly at risk are agricultural and construction workers as well as children, homeless people, the elderly, and women who have to walk long hours to collect water (*high confidence*) [13.2.1.1, 13.2.1.5, 13.2.2.4, Box 13-1]	Adaptation options are limited for people who are dependent on agriculture and too poor to afford agricultural machinery. Adaptation options are limited in the construction sector where many poor people work under insecure arrangements. Adaptation might be impossible in certain areas in a +4°C world.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	Very low / Medium / Very high
Declining agricultural yields, primarily in already hot climates, with severe impacts on countries and communities highly dependent on agriculture. Declining yields may cause further deterioration of assets: financial (savings), human (health), social (social networks), and cultural (sense of belonging and identity) (*high confidence*) [13.2.2.2, 13.2.2.4]	Adaptation by changing livelihoods away from agriculture is limited owing to poverty and marginalization. Adaptation strategies such as early or late planting, inter-cropping, and shifting crops bring mixed benefits and have limitations, often depending on household resources and access to seasonal forecasts and longer term projections. In a +4°C world, adaptation in agriculture is very limited.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	Very low / Medium / Very high
Reduced access to water for rural and urban poor people due to water scarcity and increasing competition for water (*high confidence*) [13.2.1.1, 13.2.1.3, 13.2.1.5, Box 13-1]	Adaptation through reducing water use is not an option for the large number of people already lacking adequate access to safe water. Access to water is subject to various forms of discrimination, for instance due to gender and location. Poor and marginalized water users are unable to compete with water extraction by industries, large-scale agriculture, and other powerful users.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	Very low / Medium / Very high

Projections of future climate change impacts on gross domestic product (GDP) use non-disaggregated poverty data. For instance, Mendelsohn et al. (2006) use dynamic coupled ocean-atmosphere models and market response functions to simulate the distribution of climate impacts for 2100. Independent of the climate scenarios, poor countries, mainly in Africa and Southeast Asia, will face the largest losses (0.2 to 1.2% reduction in GDP) and, under experimental models, up to 23.8% drop in GDP; in contrast, the richest quartile will encounter both positive and negative effects, ranging –0.1% to +0.2% GDP, and up to a 0.9% GDP increase under experimental models. Changes in GDP reflect climate-sensitive economic sectors, especially water and energy, with poor nations in low latitudes already facing high temperatures and thus more

vulnerable to decreased agricultural productivity with increased warming. One study for the USA, using the SRES A2 scenario, projects that four climate change impacts—hurricane damage, energy costs, water costs, and real estate—are expected to cost 1.8% of the country's GDP by 2100, leading to higher household costs for basic necessities such as energy and water (Ackerman et al., 2008). Groups that spend the highest proportion of their income on these necessities will be disproportionately affected.

A growing body of literature estimates future changes in agricultural production and food prices due to climate change, variability, and extreme events (Slater et al., 2007; Thomas et al., 2007; Assuncao and Cheres, 2008; Burke et al., 2011; see Chapters 7 and 9, and Box CC-HS). Mixed trends are projected for major staples for all continents until the mid-21st century. For the near-term future, the production of coarse grains in Africa may be reduced by 17 to 22% due to climate change; well-fertilized modern seed varieties are projected to be more susceptible to heat stress than traditional ones (Schlenker and Lobell, 2010). By 2080, a major decrease in land productivity is expected for sub-Saharan Africa (–14% to –27%) and Southeast Asia (–18% to –32%), coupled with increase in water demand, while lowest risks are projected for North America, Europe, East Asia, Russia, and Australia (Iglesias et al., 2011).

13.2.2.3. Implications for Livelihood Assets, Trajectories, and Poverty Dynamics

Projections of near- and long-term climate change impacts on livelihood assets highlight the erosion of financial assets as a result of increased food prices (Ahmed et al., 2009; Seo et al., 2009; Thurlow et al., 2009; Hertel et al., 2010; Jacoby et al., 2011; Skoufias et al., 2011b), human assets due to decline in nutritional status (Liu et al., 2008), and natural assets due to lower agricultural productivity (Jones and Thornton, 2009;Thurlow et al., 2009; Skoufias et al., 2011b). They also show a substantial increase in future heat-related mortality (Basu and Samet, 2002; McGregor et al., 2006; Sherwood and Huber, 2010; Huang et al., 2011), increasing infectious disease transmission rates (Green et al., 2010), and other health impacts (see Chapter 11). Impacts on social and cultural assets have received little attention. Exceptions address losses of social identity and cultural connections with land and sea among indigenous populations threatened by sea level rise and potential relocation (Green et al., 2010) and conflicts between ethnic and/or religious groups (Adano et al., 2012; see also Chapter 12). Poor households with limited social networks will be worst off, including in places such as Nepal (Menon, 2009) and Indonesia (Skoufias et al., 2011a).

Climate change is also projected to cause shifts in livelihood trajectories. In Mali's agricultural-pastoralist transition zone, due to temperature increase and drying projected for 2025 and coupled with a 50% increase in population, shifts from rainfed millet and sorghum to semiarid, predominantly livestock subsistence are expected to expose an extra 6 million people to malnutrition, including 250,000 children suffering from stunting (Jankowska et al., 2012). Simulated probabilities of failed seasons, using current daily rainfall data and 2050 projections for the length of growing period, show transitions from cropping to livestock in other marginal cropping areas in Africa (Thomas et al., 2007; Jones and Thornton, 2009). The Met Office Hadley Centre climate prediction model 3 (HadCM3) and a high emission scenario (SRES A1F1) show that, by 2050, expanding vector populations, especially tsetse, and a greater than 20% decline in growing period, in livestock-dependent and mixed crop-livestock livelihoods in semiarid to arid Africa and Asia, combined with increasing water scarcity and stover loss due to maize substitution (Thornton et al., 2007) will stress livelihoods of poor farmers and pastoralists.

Future climate change impacts on disaggregated poverty are addressed mainly through projected changes in food prices and earnings associated with impacts on agricultural production (Schmidhuber and Tubiello, 2007). Changes in price-induced earnings lower the welfare of low-income households, particularly urban and wage-labor dependent households that use a large income share to purchase staple crops. In the near-term future, under low productivity scenarios assuming rapid temperature increase by 2030, poverty among the agricultural self-employed in 15 LICs and MICs may drop due to benefits from selling surplus production at higher prices, by as much as 40% in Chile and the Philippines; however, higher food prices may lead to a drop in national welfare, as steep as 55% in South Africa (Hertel et al., 2010). In most LICs and MICs, the poverty headcount is expected to drop in some occupational strata and increase in others; only in most African countries are yield impacts expected to be too severe to allow benefits (Hertel and Rosch, 2010). Long-term, a one-time maximum extreme dry event, simulated for 1971–2000 and 2071–2100 using the IPCC-SRES A2 scenario for 16 LICs and MICs, shows a 95 to 110% rise in poverty for urban wage groups in Malawi, Zambia, and Mexico, while self-employed farming households consolidate assets and face the smallest increase in vulnerability (Ahmed et al., 2009). By 2100, climate change would leave low-income, minority, and politically marginalized groups in California's agriculture with fewer economic opportunities, based on SRES B1 and A1FI scenarios, particularly in dairy and grape production (Cordova et al., 2006; Shonkoff et al., 2011).

13.2.2.4. Impacts on Transient and Chronic Poverty, Poverty Traps, and Thresholds

Existing projections do not provide robust evidence to estimate whether shifts from transient to chronic poverty will occur as a result of climate change, and to what extent. However, a predicted increase in the number of urban poor, especially wage laborers, suggests that a large number may shift from transient to chronic poverty owing to exposure to food price increases, or find themselves in a poverty trap, especially under scenarios with long-duration climatic shifts and prolonged droughts (Ahmed et al., 2009; Hertel et al., 2010). In Zambia, almost half of the 650,000 new poor under the worst historic 10-year period projected until 2016 are expected to be in urban areas while rural poverty remains high (Thurlow et al., 2009). In Tanzania, Ahmed et al. (2011), based on a high precipitation volatility General Circulation Model (GCM), predict up to 1.17 million new poor into the near-term future (up to 2031). Shifts in and out of poverty may occur by 2050 for small-scale coffee farmers in Central America, as suitable coffee growing areas move to higher altitudes, especially when constrained by unequal access to agro-technical and climatic information (Laderach et al., 2011).

Poor countries will face greater poverty as a result of climate change and extreme events (*medium confidence*), owing to location and low-latitude high temperatures (Mendelsohn et al., 2006) anticipated further decline in adaptive capacity combined with reductions in agricultural productivity (Iglesias et al., 2011), greater inequality and deep-rooted poverty (Jones and Thornton, 2009), and lower levels of education and large numbers of young dependents (Skoufias et al., 2011c). Although robust projections on poverty traps are lacking, they may be associated with emerging hotspots of hunger, such as those projected for Tanzania, Mozambique, and the Democratic Republic of Congo (DRC) by 2030 (Liu et al., 2008). Based on SRES scenarios, Devitt and Tol (2012) project long-term coupled climate change- and conflict-induced poverty traps for the DRC and several other sub-Saharan countries.

Some climate change projections (see Box CC-HS and WGI AR5 Chapters 11, 12, 14) indicate the possibility of large impacts that may exceed thresholds of detrimental shocks to livelihoods and poverty, unless strong adaptation and/or mitigation responses are implemented in a timely manner (Kovats and Hajat, 2008; Sherwood and Huber, 2010). Because women do most of the agricultural work, they will suffer disproportionally from heat stress; for instance, in parts of Africa, women carry out 90% of hoeing and weeding and 60% of harvesting work (Blackden and Wodon, 2006). Toward the end of the century, the risk of heat stress may become acute in parts of Africa, particularly the Sahel, and the Indian sub-continent, potentially preventing people from practicing agriculture (Patricola and Cook, 2010; Dunne et al., 2013). In the glacier-dependent Himalayan region, excessive runoff and flooding will threaten livelihoods (Xu et al., 2009). Relocation would represent a critical threshold for indigenous groups, due to sea level rise for the Torres Strait Islanders between Australia and Papua New Guinea (Green et al., 2010) and permafrost degradation and higher and seasonally erratic precipitation for the Viliui Sakha in the Russian North (Crate, 2013).

13.3. Assessment of Impacts of Climate Change Responses on Livelihoods and Poverty

Climate change responses interact with social and political processes to affect sustainable development and climate resilient pathways and in turn, livelihoods and poverty. Climate mitigation and adaptation responses include formal policies by governments, non-governmental organizations (NGOs), bilateral and multilateral organizations, as well as actions by individuals and communities. Such policy responses were designed to have positive effects on sustainable development or at least be neutral in terms of unintended side effects. Yet, much of the peer-reviewed literature scrutinizing these responses suggests otherwise. This section reviews empirical evidence of impacts of particular mitigation (Section 13.3.1) and adaptation (Section 13.3.2) responses in the context of livelihood and poverty trajectories and inequalities. Some of this evidence is preliminary as several policies are still in their infancy while other cases fail to assess multidimensional poverty or dynamic livelihood decision making in the context of climate change responses.

13.3.1. Impacts of Mitigation Responses

Many synergies between climate change mitigation policies and poverty alleviation have been identified in the literature (Klein et al., 2005; Ürge-Vorsatz and Tirado Herrero, 2012), but evidence of positive outcomes is limited. Impacts of current mitigation policies on livelihoods and poverty are controversial with polarized views on the potential of such policies for sustainable development in general and poverty alleviation in particular (Collier et al., 2008; Böhm, 2009; Hertel and Rosch, 2010; Michaelowa, 2011). This section assesses the observed and potential impacts of four climate change responses on livelihoods and poverty: the two mitigation responses most significant for poverty alleviation under the United Nations Framework Convention on Climate Change (UNFCCC), the Clean Development Mechanism (CDM) and Reduction of Emissions from Deforestation and Forest Degradation (REDD+), and two mitigation responses outside of the UNFCCC, voluntary carbon offsets and biofuel production.

13.3.1.1. The Clean Development Mechanism

The CDM (see WGIII AR5 Chapter 13) aims to promote sustainable development, thus CDM projects require approval by the host country's designated national authority. CDM projects as diverse as low-cost

Frequently Asked Questions

FAQ 13.3 | Are there unintended negative consequences of climate change policies for people who are poor?

Climate change mitigation and adaptation policies may have unintended and potentially detrimental effects on poor people and their livelihoods (the set of capabilities, assets, and activities required to make a living). Here is just one example. In part as a result of climate change mitigation policies to promote biofuels and growing concern about food insecurity in middle- and high-income countries, large-scale land acquisition in Africa, Southeast Asia, and Latin America has displaced small landholders and contributed to food price increases. Poor urban residents are particularly vulnerable to food price increases as they use a large share of their income to purchase food. At the same time, higher food prices may benefit some agricultural self-employed groups. Besides negative impacts on food security, biofuel schemes may also harm poor and marginalized people through declining biodiversity, reduced grazing land, competition for water, and unfavorable shifts in access to and control over resources. However, employment in the biofuel industry may create opportunities for some people to improve their livelihoods.

energy services in India, micro-hydro projects in Bhutan and Peru, efficient firewood use in Nigeria, and biogas digesters in China and Vietnam, are expected to generate livelihood benefits and employment, and reduce poverty among beneficiaries (UNFCCC, 2011, 2013). The secretariat's own assessment of the CDM's development benefits along 15 indicators suggested much room for improvement (UNFCCC, 2011). Most of the statistical information in official reports on CDM is based either on project documents or on surveys of project personnel rather than in-depth studies.

The assessment of the CDM in the peer-reviewed literature is more cautious and pessimistic than UNFCCC, and three reviews (Olsen, 2007; Sutter and Parreño, 2007; Michaelowa and Michaelowa, 2011) contend that the current CDM design is neither pro-poor nor contributes to sustainable development. One reason for the low performance on sustainable development criteria is that the CDM does not have any requirements for monitoring and verification of development impacts as required for emissions reductions (Boyd et al., 2009). Critiques entail obstacles and ethical dilemmas in carbon trading (Liverman, 2009; Newell and Bumpus, 2012), difficulties with implementation (Borges da Cunha et al., 2007; Minang et al., 2007; Gong, 2010), procedural limitations (Lund, 2010), and carbon offset goals favored over poverty reduction goals (Wittman and Caron, 2009). While some authors claim that the CDM undermines local and non-governmental input (Shin, 2010; Corbera and Jover, 2012), others stress its transparency, including the voices of local stakeholders (Michaelowa et al., 2012). Also, the CDM may compete with the informal sector (Newell and Bumpus, 2012) and accentuate uneven development by eroding local livelihood security (Boyd and Goodman, 2011). In a meta-analysis of 114 CDM projects, Crowe (2013) conclude that fewer than 10% of CDM projects had successfully delivered pro-poor benefits and only one of them had positive ratings on all seven criteria for pro-poor benefits. Among the most promising examples are CDM projects in India supporting community-designed plans to strengthen participation of marginalized groups (Boyd and Goodman, 2011; Subbarao and Lloyd, 2011).

13.3.1.2. Reduction of Emissions from Deforestation and Forest Degradation

Experience with REDD+ and other forest carbon projects is inadequate to permit generalizations about effects on livelihoods and poverty (Cotula et al., 2009; Hayes and Persha, 2010; Springate-Baginski and Wollenberg, 2010; see Chapter 9). A study of 20 avoided deforestation projects prior to REDD+ in Latin America, Africa, and Asia shows that only five conducted some outcome or impact assessment, revealing a lack of rigor in evaluation (Caplow et al., 2011). Despite optimism in policy analyses about the potential of REDD+ for poverty alleviation (Angelsen et al., 2009; Kanowski et al., 2011; Rahlao et al., 2012; Somorin et al., 2013), there is growing evidence and *high agreement* in the peer-reviewed literature that REDD+ may not lead to poverty alleviation and that there may even be negative consequences. Concerns include threats to the poor (Ghazoul et al., 2010; Phelps et al., 2010; Börner et al., 2011; Larson, 2011; McDermott et al., 2011; Van Dam, 2011; Mahanty et al., 2012; Neupane and Shrestha, 2012) and indigenous peoples (Shankland and Hasenclever, 2011). Latent negative impacts include exclusion of local people from forest use, and loss of local ownership in documenting the state of forests due to external monitoring and verification mechanisms (Gupta et al., 2012; Pokorny et al., 2013). Benefit flows may be unevenly distributed with regards to ethnicity (Krause and Loft, 2013), gender (Peach Brown, 2011; UN-REDD, 2011), or simply not target the poor (Hett et al., 2012). The absence of a global REDD+ mechanism means that progress on REDD+ may occur as much through voluntary bilateral and public-private processes as through multilateral, regulatory requirements (Agrawal et al., 2011). Positive future benefits for poor people from REDD+ will require attention to tenure and property rights, gender interests, and community engagement (Danielsen et al., 2011; Mustalahti et al., 2012).

The 2010 Cancun Agreements highlight safeguards for governments to observe in REDD+ implementation, such as respect for the interests, knowledge, rights, and sustainable livelihoods of communities and indigenous peoples. If these safeguards will be observed in practice is unclear owing to the early implementation state of REDD+ in most countries as well as the uncertainty of the future of the global carbon market (Lohmann, 2010; Savaresi, 2013).

13.3.1.3. Voluntary Carbon Offsets

The voluntary carbon offset (VCO) market is significant from a livelihoods and poverty perspective because it typically targets smaller projects and may be better at reaching poor communities (Estrada and Corbera, 2012), though it is modest in size compared to the regulated market (approximately 1%). Also, those involved in the VCO market, namely individuals, companies, organizations, and countries that have not ratified the Kyoto Protocol, are often more willing to pay for carbon offsets with co-benefits such as poverty alleviation (MacKerron et al., 2009).

Activities under VCO are dominated by renewable energy, primarily wind power (30%), forestation projects including REDD+ (19%), and methane destruction in landfills (7%) (Peters-Stanley and Hamilton, 2012). It is too early to tell whether these VCO projects are successful in terms of poverty alleviation and other social goals, and results to date are highly mixed (Jindal et al., 2008; Swallow and Meinzen-Dick, 2009; Jindal, 2010; Estrada and Corbera, 2012; Stringer et al., 2012). Reported benefits include livelihood diversification, increased disposable income, biodiversity conservation, and strengthening local organizations, while exacerbated inequalities and loss of access to local resources are known negative impacts (Estrada and Corbera, 2012). A study in Kenya, Senegal, and Peru shows reduced losses of soil fertility in three soil carbon sequestration projects, but also the inability of the poorest farmers to participate and only marginal impacts on poverty reduction (Antle and Stoorvogel, 2009). Out of 78 projects in 23 countries in sub-Saharan Africa, only one promoted local social, economic, and environmental benefits while the rest focused mainly on efficiency of emission reductions (Karavai and Hinostroza, 2013).

13.3.1.4. Biofuel Production and Large-Scale Land Acquisitions

Biofuel production, often linked to transnational large-scale land acquisitions (LSLA), is a near-term climate change mitigation response that raises two major livelihood and poverty concerns: food price

increases and dispossession of land (see Chapters 4, 9). LSLA have soared since 2008 (Von Braun et al., 2009; Borras Jr. et al., 2011a; Deininger et al., 2011), partly linked to climate change responses (*medium evidence*, *high agreement*). Biofuel production is considered the primary driver, but there may be links to climate change through high food prices (Daniel, 2011), food insecurity (Robertson and Pinstrup-Andersen, 2010; Rosset, 2011; Sulser et al., 2011), and carbon markets potentially raising land prices, for example, REDD+ (Cotula et al., 2009; Zoomers, 2010; Anseeuw et al., 2012). LSLA global targets are biofuels (40%), food (25%), and forestry (3%), with much regional variation (Anseeuw et al., 2012). The IPCC special report on renewable energy highlighted the uncertainties around the role of biofuels in food price increases and risks of deteriorating food security with future deployment of bioenergy (Edenhofer et al., 2011).

Increasing demand for biofuels shifts land from food to fuel production, which may increase food prices (Collier et al., 2008) disproportionally affecting the poor (Von Braun and Ahmed, 2008; Bibi et al., 2010; Ruel et al., 2010). Despite high agreement that biofuel production plays a role in food prices, little consensus exists on the size of this influence (Aksoy and Isik-Dikmelik, 2008; Elobeid and Hart, 2008; Mitchell, 2008; Von Braun and Ahmed, 2008; Baffes and Haniotis, 2010; Ajanovic, 2011; Condon et al., 2013). Some studies link the 2007/2008 price spike to speculation in agricultural futures markets (Runge and Senauer, 2007; Ghosh, 2010) driven partly by potential future profits from biofuels while their role was relatively less important in the 2010/2011 price spike (Trostle et al., 2011).

LSLA have also triggered a land rush in LICs, which affects livelihood choices and outcomes, with some distinct gender dimensions (Chu, 2011; De Schutter, 2011; Julia and White, 2012; Peters, 2013). New competition for land dispossesses smallholders, displaces food production, degrades the environment, and pushes poor people onto more marginal lands less adaptable to climatic stressors (Cotula et al., 2009; Borras Jr. et al., 2011a; Rulli et al., 2013; Weinzettel et al., 2013). The expansion of bioenergy, and biofuels in particular, increases the corporate power of international actors over governments and local actors with harmful effects on national food and agricultural policies (Dauvergne and Neville, 2009; Glenna and Cahoy, 2009; Hollander, 2010; Mol, 2010; Fortin, 2011; Jarosz, 2012), further marginalizing smallholders (Ariza-Montobbio et al., 2010; De Schutter, 2011; Neville and Dauvergne, 2012) and indigenous peoples (Montefrio, 2012; Obidzinski et al., 2012; Manik et al., 2013; Montefrio and Sonnenfeld, 2013). There is growing apprehension that increased competition for scarce land undermines women's access to land and their ability to benefit economically from biofuel investment (Arndt et al., 2011; Chu, 2011; Molony, 2011; Behrman et al., 2012; Julia and White, 2012; Perch et al., 2012). Concerns differ somewhat among regions, with the greatest risk for negative outcomes for smallholders in Africa (Daley and Englert, 2010; Borras et al., 2011b).

Mainstream economic modeling offers optimism that biofuels may boost investment, employment, and economic growth in LICs such as Mozambique (Arndt et al., 2009) and MICs such as India (Gopinathan and Sudhakaran, 2011) and Thailand (Silalertruksa et al., 2012) yet limited evidence exists on potential benefits being realized. A major government initiative to promote jatropha cultivation in India has failed (Kumar et al., 2011) and in some cases has left rural people worse off (Bastos Lima, 2012), whereas in Malawi it offered supplemental livelihood opportunities (Dyer et al., 2012). Even though income and employment in Brazil may have increased due to ethanol production (Ferreira and Passador, 2011), structural inequalities in the sector remain (Peskett, 2007; Hall et al., 2009; Bastos Lima, 2012). Biofuel production in itself will not transform living conditions in rural areas without being integrated into development policies (Hanff et al., 2011; Dyer et al., 2012; Jarosz, 2012).

13.3.2. Impacts of Adaptation Responses on Poverty and Livelihoods

Local responses to climate variability, shocks, and change have always been part of livelihoods (Morton, 2007). Formal policy responses to climate change, however, have developed more recently as the urgency of adaptation, in addition to mitigation, became a clear international policy mandate (Pielke Jr. et al., 2007). Even well-intentioned adaptation projects (see Chapters 14 to 16) and efforts may have unintended and sometimes detrimental impacts on livelihoods and poverty, and may exacerbate existing inequalities. This section assesses the near-term effects of autonomous and planned adaptation and formal insurance schemes on the livelihoods of poor populations. Because adaptation policies and projects are relatively recent, understanding of their long-term effects is very limited.

13.3.2.1. Impacts of Adaptation Responses on Livelihoods and Poverty

Autonomous adaptation strategies—such as diversification of livelihoods (Smith et al., 2000; Mertz et al., 2009), migration (McLeman and Smit, 2006; Tacoli, 2009; see Chapter 12), storage of food (Smit and Skinner, 2002; Howden et al., 2007), communal pooling (Linnerooth-Bayer and Mechler, 2006), market responses (Halstead and O'Shea, 2004); and saving, credit societies, and systems of mutual support (Andersson and Gabrielsson, 2012)—have been found to have positive effects on poverty reduction in certain contexts, or at least prevent further deterioration due to weather events and climate, especially when supported by policy measures (Adger et al., 2003; Urwin and Jordan, 2008; Stringer et al., 2009). Yet, some autonomous strategies such as diversification and storage are often unavailable to the poorest, who lack the required resources or surplus (Smithers and Blay-Palmer, 2001; Osbahr et al., 2008; Seo, 2010) or require more labor-intensive practices that undermine people's health and may push them over a poverty threshold (Eriksen and Silva, 2009). Moreover, autonomous adaptation strategies can increase vulnerability for others or be subject to local elite capture (McLaughlin and Dietz, 2008; Eriksen and Silva, 2009; Bhattamishra and Barrett, 2010). Men's migration in Northern Mali, for example, increases the workload of the rest of the family, especially women, and reduces children's school attendance (Brockhaus et al., 2013). There is no evidence regarding the impacts of autonomous responses on people living in poverty in MICs and HICs.

Few rigorous studies about pilot adaptation projects exist outside of organizations' own assessments (Mapfumo et al., 2010; Nkem et al., 2011) or evaluations of how planned adaptation was implemented or

integrated into development (Gagnon-Lebrun and Agrawala, 2006; Gigli and Agrawala, 2007). An assessment of the only completed Global Environment Facility/World Bank (GEF/WB)-funded adaptation project, in the Caribbean, Colombia, and Kiribati, did not directly appraise the effects on poverty and livelihoods due to scarce baseline poverty data. Other projects, such as in India's Karnataka Watershed, are said to have increased agricultural productivity, income, and employment, benefiting the poorest and landless and improving equity (IEG, 2012). National Action Plans of Adaptation tend to overemphasize technological and infrastructural measures while often overlooking poor people's needs, gender issues, and livelihood and adaptation strategies (Agrawal and Perrin, 2009; Perch, 2011).

13.3.2.2. Insurance Mechanisms for Adaptation

Insurance mechanisms (see Glossary and Chapter 10) reflect the tendency that some formal adaptation measures reach the wealthier more easily while prohibitive costs may prevent poor people from accessing such mechanisms. Nonetheless, public and private insurance systems have been proposed by the World Bank and UNFCCC as an adaptation strategy to reduce, share, and spread climate change-induced risk and smooth consumption, especially among poor households (Mechler et al., 2006; Hertel and Rosch, 2010; Akter et al., 2011; Benson et al., 2012). Formal insurance schemes can potentially provide a way out of poverty traps (Barnett et al., 2008) caused by a household's process to rebuild assets after climate shocks over years (Dercon, 2006; Hertel and Rosch, 2010).

Poor people tend not to be insured via formal institutions, though strategies such as risk spreading, social networks, local credit, asset markets, and dividing herds between kin act as informal risk management mechanisms (Barnett et al., 2008; Giné et al., 2008; Pierro and Desai, 2008; De Jode, 2010; Hertel and Rosch, 2010). Unable to access insurance, they often invest in low-risk, low-return livelihood activities, which makes asset accumulation to escape chronic poverty very difficult (Elbers et al., 2007; Barnett et al., 2008). As a response, new insurance mechanisms such as micro-insurance directed at low-income people and weather index insurance for crops and livestock (see also Chapter 10) have emerged, showing mixed results (Barnett et al., 2008; Mahul et al., 2009; Akter et al., 2011; Matsaert et al., 2011; Biener and Eling, 2012).

Experiences from South Asia and several African countries illustrate positive effects of micro-insurance on investment, production, and income under drought and flood risk, including possible longer-term impacts on future income-earning activities and health, although affordability may limit the potential for the poorest (Yamauchi et al., 2009; Hochrainer-Stigler et al., 2012; Karlan et al., 2012; Tadesse and Brans, 2012). There is emerging evidence that weather index insurance can be specifically designed to reach the people usually uninsurable, for example, by premium-for-work arrangements. In such arrangements farmers provide labor and in return get an insurance certificate against rain failure in a crucial growth period for their staple crops (Brans et al., 2011). Slow uptake of insurance among poor people may be related to farmers not fully understanding the schemes' merits and function or not trusting that payouts will come (Giné and Yang, 2009; Patt et al., 2010).

13.4. Implications of Climate Change for Poverty Alleviation Efforts

This section assesses how climate change may affect efforts to alleviate poverty. Evidence from observed impacts and projections highlight both challenges and opportunities. The section builds on the findings from Sections 13.1 to 13.3 and stresses the need to take into account the complexity of livelihood dynamics, multidimensional poverty, and intersecting inequalities to successfully navigate climate-resilient development pathways (see Glossary).

Observed impacts of weather events and climate on livelihoods and poverty and impacts projected from the subnational to the global level suggest that livelihood well-being, poverty alleviation, and development are already undermined and will continue to be eroded into the future (*high confidence*). Climate change will slow down the pace of poverty reduction, jeopardize sustainable development, and undermine food security (*high confidence*; Hope, 2009;Stern, 2009; Thurlow et al., 2009; Iglesias et al., 2011; Skoufias et al., 2011b). Currently poor and food-insecure regions will continue to be disproportionately affected into the future (*high agreement*; Challinor et al., 2007; Assuncao and Cheres, 2008; Lobell et al., 2008; Liu et al., 2008; Thornton et al., 2008; Jones and Thornton, 2009; Menon, 2009; Nordhaus, 2010; Burke et al., 2011; Jacoby et al., 2011; Skoufias et al., 2011a; Adano et al., 2012). Poorer countries will experience declining adaptive capacity, which will hamper development (*high confidence*). Posey (2009) flags lower adaptive capacities in communities with concentrations of racial minorities and low-income households than in more affluent areas, due to marginalization and multidimensional inequality. Iglesias et al. (2011) project continental disparities in agricultural productivity under progressively severe climate change scenarios with highest risks for Africa and Southeast Asia. Although there is *high agreement* about the heterogeneity of future impacts on poverty, few studies consider more diverse climate change scenarios (Skoufias et al., 2011b) or the potential of 4°C and beyond (New et al., 2011). The World Bank (2012b, p. 65) states that "climate change in a four degree world could seriously undermine poverty alleviation in many regions."

13.4.1. Lessons from Climate-Development Efforts

Two key models have attempted to integrate climate and poverty concerns into development efforts: mainstreaming adaptation into development priorities and pro-poor adaptation (see Chapters 14 to 16, 20). Lessons from "adaptation as development," in which development is seen as the basis for adaptation, and "adaptation plus development," in which development interventions address future climate threats (Ayers and Dodman, 2010), typify the disagreement in policy spheres about what sustainability constitutes (Le Blanc et al., 2012) and the practical gulf between climate change policy and development spheres (Ayers and Dodman, 2010). To date, observed and projected climate change impacts are not systematically integrated into poverty reduction programs, although such integration could result in substantial resilience to covariate and idiosyncratic shocks and stresses (Brans et al., 2011; Béné et al., 2012). At the same time, science and policy emphasis on rapid-onset events, sectoral impacts, and poverty statistics has diverted attention from threats to sustainability and resilient pathways. Even

Box 13-2 | Lessons from Social Protection, Disaster Risk Reduction, and Energy Access

Social protection (SP): Considerable challenges emerge at the intersection of climate change adaptation, disaster risk reduction, and social protection. SP programs include public and private initiatives that transfer income or assets to poor people, protect against livelihood risks, and raise the social status and rights of the marginalized (see Glossary). Cash transfer programs are among the principal instruments used by governments for poverty alleviation (Barrientos and Hulme, 2009; Barrientos, 2011; Niño-Zarazúa, 2011). There is *medium agreement* among scholars and practitioners that SP helps people in chronic poverty reduce risk and protect assets during crises (Devereux et al., 2010, 2011; Barrientos, 2011; Dercon, 2011). At the regional and municipal level, SP often fails to address local government capacity to ensure risk reduction by providing water, sanitation, drainage, health care, and emergency services. Also, SP does not intentionally strengthen local collective capacity to proactively address climate change risks and take action (Satterthwaite and Mitlin, 2013).

SP that supports pro-poor climate change adaptation and disaster risk reduction by strengthening the resilience of vulnerable populations to shocks is labeled "adaptive social protection" (ASP) (Davies et al., 2009). ASP should be understood as a framework rather than a package of specific measures. ASP has almost exclusively focused on LICs and some MICs with very little attention to poor people in HICs. Few studies exist on the effectiveness of ASP for addressing incremental climatic changes and rapid-onset events, and the changing nature of climate risks as part of dynamic livelihood trajectories (Heltberg et al., 2009; Arnall et al., 2010; Bee et al., 2013). The Productive Safety Net Program in Ethiopia, for instance, had positive effects on household food consumption and asset protection (Devereux et al., 2006; Slater et al., 2006). Yet, this and programs such as Brazil's *Bolsa Familia* and *Bolsa Verde* (UNDP, 2012) offer few concrete pathways to tackling systemic vulnerabilities and inequalities that inhibit effective responses to severe shocks, though they stress the role of local governments in addressing long-term livelihood security and well-being in addition to short-term disaster relief (Gilligan et al., 2009; Conway and Schipper, 2011; Béné et al., 2012; UNDP, 2012). Local governments in urban contexts have limited capacities to address livelihood security, but more scope to increase resilience through risk-reducing infrastructure (Satterthwaite and Mitlin, 2013).

Disaster risk reduction (DRR): The development and application of DRR (see Glossary) has been among the most important routes for highlighting risks of extreme weather among local governments and civil society, and came to the fore as the concentration of disaster deaths from extreme weather in LICs and MICs became evident (UNISDR, 2009, 2011). However, the accumulated effect of several small-scale events is often more damaging than large-scale ones (Aryal, 2012). DRR is now increasingly employed as an adaptation measure, for example, through community-based climate risk reduction (Tompkins et al., 2008; McSweeney and Coomes, 2011; Meenawat and Sovacool, 2011; IPCC, 2012b) and has helped identify DRR roles for local governments (IFRC, 2010). Yet, sometimes disaster management-oriented adaptation can favor property and investments of the relatively richer and divert attention and funding from measures that address disadvantaged people, as suggested in a case study of Vietnam (Buch-Hansen, 2013). The effectiveness of DRR in supporting pro-poor climate change adaptation will depend on governance structures to address changing risk contexts in policies and investments while responding to the needs and priorities of their low-income population. Lessons learned from Hurricane Katrina and the Tōhoku earthquake and tsunami showcase the multiplier effect of a disaster on top of underlying structural inequalities. Their persistence years later, as witnessed with Katrina (Schwartz, 2007; Zottarelli, 2008; Fussell et al., 2010) further stresses the need for expanded analyses beyond disaster events themselves and the recognition of the many factors that perpetuate the vicious cycle of poverty, multidimensional deprivation, and inequality.

Energy access: Energy is critical for rural development (Barnes et al., 2010; Kaygusuz, 2011, 2012) and for alleviation of urban poverty (Parikh et al., 2012). One proposed climate-resilient pathway is to boost renewable energy use, which could increase energy access for billions of people currently without access to safe and efficient energy while cutting greenhouse gas emissions from rising non-renewable energy consumption (Casillas and Kammen, 2010; Edenhofer et al., 2011). Benefits include better health (see also Chapter 11), employment, and cost savings relative to fossil fuels (Edenhofer et al., 2011; Jerneck and Olsson, 2012).

where legal reforms to secure the rights of poor people exist, as in Mexico's Climate Law, inequalities persist (MacLennan and Perch, 2012). Without addressing the climatic, social, and environmental stressors that shape livelihood trajectories, including poverty traps (see Figure 13-2), and the underlying causes of poverty, persistent inequalities, and uneven resource access and institutional support, adaption efforts and policies will be nothing more than temporary fixes. Poverty alleviation alone will not necessarily lead to more equality (Pogge, 2009; Milanovic, 2012). Box 13-2 provides insight into three examples.

13.4.2. Toward Climate-Resilient Development Pathways

Given the multiple challenges at the climate-poverty-development nexus, debates increasingly focus on transforming the development pathways themselves toward greater social and environmental sustainability, equity, resilience, and justice, calling for a fundamental shift toward near- and long-term climate-resilient development pathways (see Chapter 20). This perspective acknowledges the shortcomings in dominant global development pathways, above all rising levels of consumption and emissions, privatization of resources, and limited capacities of local governments and civil society to counter these trends (Pelling, 2010; Eriksen et al., 2011; O'Brien, 2012; UN, 2012a).

At Rio+20 in 2012, an Open Working Group was created by the UN General Assembly to develop Sustainable Development Goals (SDGs) building on the Millennium Development Goals (MDGs), which are criticized for not explicitly addressing the root causes of poverty, inequality, or climate change (Melamed, 2012; UN, 2012b) and the anticipated failure to reach MDG 1 (eradicate extreme poverty and hunger by 2015), with or without climate change (Tubiello et al., 2008). Early SDG debates reveal a stronger focus on eradicating extreme poverty and environmental problems facing poor people (UN, 2012a). This framing of development acknowledges shared global futures that require collective action from the richest, not merely promoting welfare for the poorest, to address both climate change and poverty (Ayers and Dodman, 2010; UN, 2012a,b). Little information exists to date to project how these SDGs will support climate-resilient development pathways. Formulating goals, however, will not suffice unless the global institutional framework for sustainable development is radically reformed (Biermann et al., 2012).

Paying attention to dynamic livelihoods and multidimensional poverty and the multifaceted impacts of climate change and climate change responses is central to achieving climate-resilient development pathways (see Chapter 20). Evidence from Sections 13.2 and 13.3 suggests that increasing global inequality, new poverty in MICs and HICs, and more people shifting from transient to chronic poverty overlaid with business-as-usual development and climate policies will bring poor and marginalized people precariously close to the two most undesirable future scenarios as conceptualized in the shared socioeconomic pathways (SSPs) (see Chapter 1): social fragmentation (fragmented world) and inequality (unequal world). At the community level, inadequate governance structures and elite capture often propel less affluent households into deeper poverty. There is *high agreement* among scholars of global governance that fragmentation also exists at the level of the global climate regime (Biermann, 2010; Roberts, 2011; Mol, 2012), rooted in entrenched inequalities (Parks and Roberts, 2010). The extent to which fragmentation promotes positive or negative outcomes of climate and development goals is contested, ranging from polycentric governance modes (Ostrom, 2010) to conflictive fragmentation (Biermann et al., 2009; Mittelman, 2013). Evidence from this chapter suggests that, in order to move toward the mid- and long-term SSP 1 (sustainability), a fundamental rethinking of poverty and development will need to emphasize equity among poor and non-poor people to collectively address greenhouse gas emissions and vulnerabilities while striving toward a joint, just, and desirable future.

13.5. Synthesis and Research Gaps

Previous IPCC reports have stated that climate change would cause disproportionally adverse effects for the world's poor people. However, they presented a rather generalized view that all poor people were vulnerable, in contrast to earlier scientific studies highlighting vulnerability as contextual with variation over time and space. This chapter is devoted to exploring poverty in relation to climate change, a new theme in the IPCC. It uses a livelihood lens to assess the interactions between climate change and the multiple dimensions of poverty, not just income poverty. This lens also reveals how inequalities perpetuate poverty, and how they shape differential vulnerabilities and in turn the differentiated impacts of climate change on individuals and societies. This chapter illustrates that climate change adds an additional burden to poor people and their livelihoods, acting as a threat multiplier. Moreover, it emphasizes that climate change may create new groups of poor people, not only in low-income countries but also in middle- and high-income countries. Neither alleviating poverty nor decreasing vulnerabilities to climate change can be achieved unless entrenched inequalities are reduced. This chapter concludes that climate change policy responses reviewed in this chapter often do not benefit poor people, and highlights lessons for climate-resilient development pathways.

Eight major research gaps are identified with respect to the observed and projected impacts of climate change and climate change responses:

- Poverty dynamics are not sufficiently accounted for in current climate change research. Most research as well as poverty measurements remain focused on only one or two dimensions of poverty. Insufficient work assesses the distribution of poverty at the level of households, spatial and temporal shifts, critical thresholds that plunge some transient poor into chronic poverty, and poverty traps, in the context of climatic and non-climatic stressors. Many of these dynamics remain hidden, incompletely captured in poverty statistics and disaster and development discourses. Key assumptions in many economic models (e.g., constant within-country distribution of per capita income over time, linear relationship between economic growth and poverty headcounts) are ill suited to capture local and subnational poverty dynamics, confounding projections of future poverty levels.
- Though an abundance of studies exists that explore climate change impacts on livelihoods, the majority does not focus on continuous struggles and trajectories but only offers snapshots. An explicit analysis of livelihood dynamics would more clearly reveal how people respond to a series of climatic stressors and shocks over time.

- Few studies examine how structural inequalities, power imbalances, and intersecting axes of privilege and marginalization shape differential vulnerabilities to climate change. Although there is growing literature on climate change and gender as well as on indigeneity, other axes such as age, class, race, caste, and (dis)ability, remain underexplored. Understanding how simultaneous and intersecting inequalities determine climate change impacts shows which particular drivers of vulnerability are at play in one context, while absent in another.
- Very limited research examines climate change impacts on poor people and livelihoods in middle- to high-income countries. Despite mounting evidence of observed impacts of climatic events on the poor in MICs and HICs, as documented for the European heat wave, Hurricane Katrina in the USA, and the 10-year drought in Australia, the majority of research on the poverty-climate nexus remains focused on the poorest countries.
- There remains a lack of rigorous data collection and analysis regarding small-scale disasters, that is, those that go unnoticed because of their limited extent, but whose accumulated effect may exceed large-scale disasters. This gap leads to significant underestimation of lived experiences with climate change, in which particular loss and harm remain largely undetected. There is a need for more climatology research informed by the needs of poor people and vulnerable livelihoods, for instance on the effects of changing winds as a combined result of climate and land cover change, and their effects on increasing evaporation and water availability.
- Not enough consideration is given to extreme stressors and shocks, for example, under potential global mean warming of +4°C and beyond, underestimating impacts on poor and marginalized people and limits to adaptation.
- There is a lack of in-depth research on the direct and indirect effects of mitigation and adaptation climate-related policies such as CDM, REDD+, biofuels, and insurance on livelihoods, poverty, and inequality. More in-depth research has the potential to improve the capacity of these policies to benefit poor people.
- Limited understanding exists of how poverty alleviation and more equality between the poor and the non-poor are best built into climate-resilient development pathways to strive toward a just and desirable future for all.

References

Abam, T., C. Ofoegbu, C. Osadebe, and A. Gobo, 2000: Impact of hydrology on the Port-Harcourt – Patani-Warri Road. *Environmental Geology*, **40(1-2)**, 153-162.

Ackerman, F., E.A. Stanton, C. Hope, S. Alberth, J. Fisher, and B. Biewald, 2008: *The Cost of Climate Change: What We'll Pay if Global Warming Continues Unchecked.* Natural Resources Defense Council, New York, NY, USA, 33 pp.

Adano, W.R., T. Dietz, K. Witsenburg, and F. Zaal, 2012: Climate change, violent conflict and local institutions in Kenya's drylands. *Journal of Peace Research*, **49(1)**, 65-80.

Adelekan, I.O., 2010: Vulnerability of poor urban coastal communities to flooding in Lagos, Nigeria. *Environment and Urbanization*, **22(2)**, 433-450.

Adger, W.N., 2010: Climate change, human well-being and insecurity. *New Political Economy*, **15(2)**, 275-292.

Adger, W.N., S. Huq, K. Brown, D. Conway, and M. Hulme, 2003: Adaptation to climate change in the developing world. *Progress in Development Studies*, **3(3)**, 179-195.

Adger, W.N., S. Agrawala, M.M.Q. Mirza, C. Conde, K. O'Brien, J. Pulhin, R. Pulwarty, B. Smit, and K. Takahashi, 2007: Chapter 17: Assessment of adaptation practices, options, constraints and capacity. In: *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate* Change [Core Writing Team, Pachauri, R.K and A. Reisinger (eds.)]. IPCC, Geneva, Switzerland, pp. 719-743.

Adrian, R., C.M. O'Reilly, H. Zagarese, S.B. Baines, D.O. Hessen, W. Keller, D.M. Livingstone, R. Sommaruga, D. Straile, and E. Van Donk, 2009: Lakes as sentinels of climate change. *Limnology and Oceanography*, **54(6)**, 2283-2297.

Agrawal, A. and N. Perrin, 2009: Climate adaptation, local institutions and rural livelihoods. In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, W.N., I. Lorenzoni, and K.L. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 350-367.

Agrawal, A., D. Nepstad, and A. Chhatre, 2011: Reducing emissions from deforestation and forest degradation. *Annual Review of Environment and Resources*, **36(1)**, 373-396.

Ahearn, L.M., 2001: *Invitations to Love: Literacy, Love Letters, and Social Change in Nepal.* University of Michigan Press, Ann Arbor, MI, USA, 295 pp.

Ahmed, A.U., S.R. Hassan, B. Etzold, and S. Neelormi, 2012: *Rainfall, Food Security and Human Mobility, Bangladesh Case Study.* UNU-EHS Report 2, the United Nations University-Institute for Environment and Human Security (UNU-EHS) and CARE, UNU-EHS, Bonn, Germany, 158 pp.

Ahmed, S.A., N.S. Diffenbaugh, and T.W. Hertel, 2009: Climate volatility deepens poverty vulnerability in developing countries. *Environmental Research Letters*, **4(3)**, 034004, doi:10.1088/1748-9326/4/3/034004.

Ahmed, S.A., N.S. Diffenbaugh, T.W. Hertel, D.B. Lobell, N. Ramankutty, A.R. Rios, and P. Rowhani, 2011: Climate volatility and poverty vulnerability in Tanzania. *Global Environmental Change*, **21(1)**, 46-55.

Ajanovic, A., 2011: Biofuels versus food production: does biofuels production increase food prices? *Energy*, **36(4)**, 2070-2076.

Aksoy, A. and A. Isik-Dikmelik, 2008: *Are Low Food Prices Pro-Poor? Net Food Buyers and Sellers in Low-Income Countries.* Policy Research Working Paper 4642, the Trade Team, Development Research Group, the International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 30 pp.

Akter, S., R. Brouwer, P.J.H. van Beukering, L. French, E. Silver, S. Choudhury, and S.S. Aziz, 2011: Exploring the feasibility of private micro flood insurance provision in Bangladesh. *Disasters*, **35(2)**, 287-307.

Alderman, H., 2010: Safety nets can help address the risks to nutrition from increasing climate variability. *The Journal of Nutrition*, **140(Suppl. 1)**, 148S-152S.

Alkire, S., 2005: *Valuing Freedoms: Sen's Capability Approach and Poverty Reduction.* Oxford University Press, Oxford, UK and New York, NY, USA, 340 pp.

Alkire, S. and J. Foster, 2011: Understandings and misunderstandings of multidimensional poverty measurement. *Journal of Economic Inequality*, **9(2)**, 289-314.

Alkire, S. and M.E. Santos, 2010: *Acute Multidimensional Poverty: A New Index for Developing Countries.* UNDP Human Development Research Paper 2010/11, United Nations Development Programme (UNDP), New York, NY, USA, 138 pp.

Alston, M. and K. Whittenbury, 2013: *Research, Action and Policy: Addressing the Gendered Impacts of Climate Change.* Springer Science, Dordrecht, Netherlands, 281 pp.

Alston, M., 2011: Gender and climate change in Australia. *Journal of Sociology*, **47(1)**, 53-70.

Anastario, M., N. Shebab, and L. Lawry, 2009: Increased gender-based violence among women internally displaced in Mississippi 2 years post-Hurricane Katrina. *Disaster Medicine and Public Health Preparedness*, **3(1)**, 18-26.

Andersen, L. and D. Verner, 2009: *Social Impacts of Climate Change in Bolivia: A Municipal Level Analysis of the Effects of Recent Climate Change on Life Expectancy, Consumption, Poverty and Inequality.* Policy Research Working Paper 5092, the Social Development Division, Sustainable Development Department, the International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 26 pp.

Anderson, D.M. and V. Broch-Due, 2000: *The Poor Are Not Us: Poverty and Pastoralism in Eastern Africa.* James Currey, Ltd., Woodbridge, UK, 276 pp.

Anderson, D., 2009: Enduring drought then coping with climate change: lived experience and local resolve in rural mental health. *Rural Society*, **19(4)**, 340-352.

Anderson, S., J. Morton, and C. Toulmin, 2009: Climate change for agrarian societies in drylands: implications and future pathways. In: *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World* [Mearns, R. and A. Morton (eds.)]. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, pp. 199-230.

Andersson, E. and S. Gabrielsson, 2012: 'Because of poverty, we had to come together': collective action for improved food security in rural Kenya and Uganda. *International Journal of Agricultural Sustainability*, **10(3)**, 245-262.

Angelsen, A., M. Brockhaus, and M. Kanninen (eds.), 2009: *Realizing REDD+: National Strategy and Policy Options.* Center for International Forestry Research (CIFOR), Copenhagen, Denmark, 426 pp.

Anseeuw, W., L.A. Wily, L. Cotula, and M. Taylor, 2012: *Land Rights and the Rush for Land: Findings of the Global Commercial Pressures on Land Research Project.* International Land Coalition Secretariat, Rome, Italy, 72 pp.

Antle, J.M. and J.J. Stoorvogel, 2009: Payments for ecosystem services, poverty and sustainability: the case of agricultural soil carbon sequestration. *Natural Resource Management and Policy*, **31**, 133-161.

Apata, T.G., K. Samuel, and A. Adeola, 2009: *Analysis of Climate Change Perception and Adaptation among Arable Food Crop Farmers in South Western Nigeria*. Contributed paper prepared for presentation at the International Association of Agricultural Economists' 2009 Conference, Beijing, China, August 16-22, 2009, 15 pp., ageconsearch.umn.edu/bitstream/51365/2/final%20IAAE%20doc..pdf.

Ariza-Montobbio, P., S. Lele, G. Kallis, and J. Martinez-Alier, 2010: The political ecology of Jatropha plantations for biodiesel in Tamil Nadu, India. *The Journal of Peasant Studies*, **37(4)**, 875-897.

Armah, F.A., J.O. Odoi, G.T. Yengoh, S. Obiri, D.O. Yawson, and E.K.A. Afrifa, 2011: Food security and climate change in drought-sensitive savanna zones of Ghana. *Mitigation and Adaptation Strategies for Global Change*, **16(3)**, 291-306.

Arnall, A., K. Oswald, M. Davies, T. Mitchell, and C. Coirolo, 2010: *Adaptive Social Protection: Mapping the Evidence and Policy Context in the Agriculture Sector in South Asia.* IDS Working Paper No. 345, Centre for Social Protection, Institute of Development Studies (IDS), University of Sussex, Brighton, UK, 92 pp.

Arndt, C., R. Benfica, F. Tarp, J. Thurlow, and R. Uaiene, 2009: Biofuels, poverty, and growth: a computable general equilibrium analysis of Mozambique. *Environment and Development Economics*, **15(1)**, 81-105.

Arndt, C., R. Benfica, and J. Thurlow, 2011: Gender implications of biofuels expansion in Africa: the case of Mozambique. *World Development*, **39(9)**, 1649-1662.

Arora-Jonsson, S., 2011: Virtue and vulnerability: discourses on women, gender and climate change. *Global Environmental Change*, **21(2)**, 744-751.

Aryal, K.R., 2012: The history of disaster incidents and impacts in Nepal 1900-2005. *International Journal of Disaster Risk Science*, **3(3)**, 147-154.

Assuncao, J.J. and F.F. Cheres, 2008: *Climate Change, Agricultural Productivity and Poverty.* Background Paper for De La Torre, A., P. Fajnzylber, and J. Nash (2009), *Low Carbon, High Growth – Latin American Responses to Climate Change: An Overview*. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 36 pp.

Ayers, J. and D. Dodman, 2010: Climate change adaptation and development I: the state of the debate. *Progress in Development Studies*, **10(2)**, 161-168.

Ayers, J. and S. Huq, 2009: *Community-Based Adaptation to Climate Change: An Update.* IIED Briefing, International Institute for Environment and Development (IIED), London, UK, 4 pp.

Azhar-Hewitt, F. and K. Hewitt, 2012: Technocratic approaches and community contexts: viewpoints of those most at risk from environmental disasters in mountain areas, Northern Pakistan. In: *Climate Change Modeling for Local Adaptation in the Hindu Kush-Himalayan Region* [Lamadrid, A. and I. Kelman (eds.)]. Emerald Group Publishing, Ltd., Bingley, UK, pp. 53-73.

Babugura, A., 2010: *Gender and Climate Change: South Africa Case Study.* Heinrich Böll Foundation, Regional Office Southern Africa, Cape Town, South Africa, 76 pp.

Baccini, M., A. Biggeri, G. Accetta, T. Kosatsky, K. Katsouyanni, A. Analitis, H.R. Anderson, L. Bisanti, D. D'Ippoliti, and J. Danova, 2008: Heat effects on mortality in 15 European cities. *Epidemiology*, **19(5)**, 711-719.

Baffes, J. and T. Haniotis, 2010: *Placing the 2006/08 Commodity Price Boom into Perspective*. Policy Research Working Paper 5371, Development Prospects Group, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 40 pp.

Balbus, J.M. and C. Malina, 2009: Identifying vulnerable subpopulations for climate change health effects in the United States. *Journal of Occupational and Environmental Medicine*, **51(1)**, 33-37.

Balk, D., M. Montgomery, G. McGranahan, and M. Todd, 2009: Understanding the impacts of climate change: linking satellite and other spatial data with population data. In: *Population Dynamics and Climate Change* [Guzmán, J.M., G. Martine, G. McGranahan, D. Schensul, and C. Tacoli (eds.)]. The United Nations Population Fund (UNFPA), New York, NY, USA and the International Institute for Environment and Development (IIED), London, UK, pp. 206-217.

Bandiera, O., I. Barankay, and I. Rasul, 2005: Cooperation in collective action. *Economics of Transition*, **13(3)**, 473-498.

Banik, D., 2009: Legal empowerment as a conceptual and operational tool in poverty eradication. *Hague Journal on the Rule of Law*, **1(1)**, 117-131.

Barnes, D., S. Khandker, and H.A. Samad, 2010: *Energy Access, Efficiency, and Poverty: How Many Households are Energy Poor in Bangladesh?* Policy Research Paper 5332, Agriculture and Rural Development Team, Development Research Group, The International Bank for Reconstruction and Development / The World Bank, Washington. DC, USA, 48 pp.

Barnett, B.J., C.B. Barrett, and J.R. Skees, 2008: Poverty traps and index-based risk transfer products. *World Development*, **36(10)**, 1766-1785.

Barnett, J. and S. O'Neill, 2010: Maladaptation. *Global Environmental Change*, **20(2)**, 211-213.

Barrett, C. and J. McPeak, 2006: Poverty traps and safety nets. In: *Poverty, Inequality and Development* [Thorbecke, E., A. De Janvry, and S.M. Ravi Kanbur (eds.)]. Springer, New York, NY, USA, pp. 131-154.

Barrientos, A., 2011: Social protection and poverty. *International Journal of Social Welfare*, **20(3)**, 240-249.

Barrientos, A. and D. Hulme, 2009: Social protection for the poor and poorest in developing countries: reflections on a quiet revolution. *Oxford Development Studies*, **37(4)**, 439-456.

Barron, J., J. Rockström, F. Gichuki, and N. Hatibu, 2003: Dry spell analysis and maize yields for two semi-arid locations in east Africa. *Agricultural and Forest Meteorology*, **117(1-2)**, 23-37.

Bartlett, S., 2008: Climate change and urban children: impacts and implications for adaptation in low-and middle-income countries. *Environment and Urbanization*, **20(2)**, 501-519.

Bastos Lima, M.G., 2012: *An Institutional Analysis of Biofuel Policies and their Social Implications: Lessons from Brazil, India and Indonesia.* Occasional Paper No. 9, Social Dimensions of Green Economy and Sustainable Development, UN Research Institute for Social Development (UNRISD), Geneva, Switzerland, 13 pp.

Basu, R. and J.M. Samet, 2002: Relation between elevated ambient temperature and mortality: a review of the epidemiologic evidence. *Epidemiologic Reviews*, **24(2)**, 190-202.

Batterbury, S., 2001: Landscapes of diversity: a local political ecology of livelihood diversification in south-western Niger. *Cultural Geographies*, **8(4)**, 437-464.

Bebbington, A., 1999: Capitals and capabilities: a framework for analyzing peasant viability, rural livelihoods and poverty. *World Development*, **27(12)**, 2021-2044.

Bee, B., M. Biermann, and P. Tschakert, 2013: Gender, development, and rights-based approaches: lessons for climate change adaptation and adaptive social protection. In: *Research, Action and Policy: Addressing the Gendered Impacts of Climate* Change [Alston, M. and K. Whittenbury (eds.)]. Springer, Dordrecht, Netherlands, pp. 95-108.

Behrman, J., R. Meinzen-Dick, and A. Quisumbing, 2012: The gender implications of large-scale land deals. *Journal of Peasant Studies*, **39(1)**, 49-79.

Bele, M.Y., A.M. Tiani, O.A. Somorin, and D.J. Sonwa, 2013: Exploring vulnerability and adaptation to climate change of communities in the forest zone of Cameroon. *Climatic Change*, **119(3-4)**, 1-15.

Bell, J., M. Brubaker, K. Graves, and J. Berner, 2010: Climate change and mental health: uncertainty and vulnerability for Alaska natives. *Center for Climate and Health (CCH) Bulletin*, **3**, April 15, 2010, www.anthc.org/chs/ces/climate/upload/CCH-Bulletin-No-3-Mental-Health.PDF.

Béné, C., S. Devereux, and R. Sabates-Wheeler, 2012: *Shocks and Social Protection in the Horn of Africa: Analysis from the Productive Safety Net Programme in Ethiopia*. IDS Working Paper, Vol. 2012, No. 395, Center for Social Protection (CSP) Working Paper No. 005, Institute of Development Studies (IDS), University of Sussex, Brighton, UK, 120 pp.

Beniston, M., 2003: Climatic change in mountain regions: a review of possible impacts. *Climatic Change*, **59(1)**, 5-31.

Benson, C., M. Arnold, A. de la Fuente, and R. Mearns, 2012: *Financial Innovations for Social and Climate Resilience: Establishing an Evidence Base.* Social Resilience & Climate Change Brief, The World Bank, Washington, DC, USA, 2 pp.

Bhattamishra, R. and C.B. Barrett, 2010: Community-based risk management arrangements: a review. *World Development*, **38(7)**, 923-932.

Bibi, S., J. Cockburn, M. Coulibaly, and L. Tiberti, 2010: The impact of the increase in food prices on child poverty and the policy response in Mali. In: *Child Welfare in Developing Countries* [Cockburn, J. and J. Kabubo-Mariara (eds.)]. Springer Science, Dordrecht, Netherlands and New York, NY, USA, pp. 247-296.

Biener, C. and M. Eling, 2012: Insurability in microinsurance markets: an analysis of problems and potential solutions. *The Geneva Papers on Risk and Insurance Issues and Practice*, **37(1)**, 77-107.

Biermann, F., 2010: Beyond the intergovernmental regime: recent trends in global carbon governance. *Current Opinion in Environmental Sustainability*, **2(4)**, 284-288.

Biermann, F., P. Pattberg, H. Van Asselt, and F. Zelli, 2009: The fragmentation of global governance architectures: a framework for analysis. *Global Environmental Politics*, **9(4)**, 14-40.

Biermann, F., K. Abbott, S. Andresen, K. Bäckstrand, S. Bernstein, M. Betsill, H. Bulkeley, B. Cashore, J. Clapp, and C. Folke, 2012: Navigating the Anthropocene: improving earth system governance. *Science*, **335(6074)**, 1306-1307.

Blackden, C.M. and Q. Wodon, 2006: *Gender, Time Use, and Poverty in Sub-Saharan Africa.* World Bank Working Paper No. 73, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 152 pp.

Boetto, H. and J. McKinnon, 2013: Rural women and climate change: a gender-inclusive perspective. *Australian Social Work*, **66(2)**, 234-247.

Böhm, S., 2009: *Upsetting the Offset: The Political Economy of Carbon Markets.* MayFlyBooks, London, UK, 384 pp.

Boko, M., I. Niang, A. Nyong, C. Vogel, A. Githeko, M. Medany, B. Osman-Elasha, R. Tabo, and P. Yanda, 2007: Africa. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 433-467.

Borges da Cunha, K., A. Walter, and F. Rei, 2007: CDM implementation in Brazil's rural and isolated regions: the Amazonian case. *Climatic Change*, **84(1)**, 111-129.

Börner, J., S. Wunder, S. Wertz-Kanounnikoff, G. Hyman, and N. Nascimento, 2011: *REDD Sticks and Carrots in the Brazilian Amazon: Assessing Costs and Livelihood Implications*. CCAFS Working Paper No. 8, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, Denmark, 40 pp.

Borras Jr., S.M., R. Hall, I. Scoones, B. White, and W. Wolford, 2011a: Towards a better understanding of global land grabbing: an editorial introduction. *The Journal of Peasant Studies*, **38(2)**, 209-216.

Borras Jr., S.M., J. Franco, C. Kay, and M. Spoor, 2011b: *Land Grabbing in Latin America and the Caribbean in Broader International Perspectives.* A paper prepared for and presented at the Latin America and Caribbean seminar: 'Dinámicas en el mercado de la tierra en América Latina y el Caribe', 14-15 November, 2011, United Nations Food and Agriculture Organization (FAO) Regional Office, Santiago, Chile, 54 pp.

Boyd, E. and M.K. Goodman, 2011: The clean development mechanism as ethical development? Reconciling emissions trading and local development. *Journal of International Development*, **23(6)**, 836-854.

Boyd, E. and S. Juhola, 2009: Stepping up to the climate change: opportunities in re-conceptualising development futures. *Journal of International Development*, **21(6)**, 792-804.

Boyd, E., N. Hultman, J. Timmons Roberts, E. Corbera, J. Cole, A. Bozmoski, J. Ebeling, R. Tippman, P. Mann, and K. Brown, 2009: Reforming the CDM for sustainable development: lessons learned and policy futures. *Environmental Science & Policy*, **12(7)**, 820-831.

Bradshaw, S., 2010: Women, poverty, and disasters: exploring the links through hurricane Mitch in Nicaragua. In: *The International Handbook of Gender and Poverty: Concepts, Research, Policy* [Chant, S. (ed.)]. Edward Elgar Publishing, Cheltenham, UK, pp. 627-632.

Brans, M.V., M. Tadesse, and T. Takama, 2011: Community-based solutions to the climate crisis in Ethiopia. In: *Climate Change Adaptation and International Development: Making Development Cooperation More Effective* [Fujikura, R. and M. Kawanishi (eds.)]. Earthscan, London, UK and Washington, DC, USA, pp. 217-238.

Brockhaus, M. and H. Djoudi, 2008: *Adaptation at the Interface of Forest Ecosystem Goods and Services and Livestock Production Systems in Northern Mali*. CIFOR Info-Brief No. 19, Center for International Forestry Research (CIFOR), Bogor, Indonesia, 4 pp.

Brockhaus, M., H. Djoudi, and B. Locatelli, 2013: Envisioning the future and learning from the past: adapting to a changing environment in northern Mali. *Environmental Science & Policy*, **25**, 94-106.

Brouwer, R., S. Akter, L. Brander, and E. Haque, 2007: Socioeconomic vulnerability and adaptation to environmental risk: a case study of climate change and flooding in Bangladesh. *Risk Analysis*, **27(2)**, 313-326.

Bryan, E., C. Ringler, B. Okoba, C. Roncoli, S. Silvestri, and M. Herrero, 2013: Adapting agriculture to climate change in Kenya: household strategies and determinants. *Journal of Environmental Management*, **114**, 26-35.

Buch-Hansen, M., N.N. Khanh and N.H. Anh, 2013: Paradoxes in Adaptation: Economic Growth and Socio-Economic Differentiation. A Case Study of Mid-Central Vietnam. In: *On the Frontiers of Climate and Environmental Change*. [Bruun, O. and T Casse (eds)] Springer, Heidelberg, Germany, pp. 23-41.

Buechler, S., 2009: Gender, water, and climate change in Sonora, Mexico: implications for policies and programmes on agricultural income-generation. *Gender & Development*, **17(1)**, 51-66.

Bunce, M., S. Rosendo, and K. Brown, 2010a: Perceptions of climate change, multiple stressors and livelihoods on marginal African coasts. *Environment, Development and Sustainability*, **12(3)**, 407-440.

Bunce, M., K. Brown, and S. Rosendo, 2010b: Policy misfits, climate change and cross-scale vulnerability in coastal Africa: how development projects undermine resilience. *Environmental Science & Policy*, **13(6)**, 485-497.

Burke, M., J. Dykema, D. Lobell, E. Miguel, and S. Satyanath, 2011: *Incorporating Climate Uncertainty into Estimates of Climate Change Impacts, with Applications to US and African Agriculture.* NBER Working Paper No.17092, National Bureau of Economic Research (NBER), Cambridge, MA, USA, 28 pp.

Burkett, M., 2011: The Nation *Ex-Situ*: on climate change, deterritorialized nationhood and the post-climate era. *Climate Law*, **2(3)**, 345-374.

Byg, A. and J. Salick, 2009: Local perspectives on a global phenomenon – climate change in Eastern Tibetan villages. *Global Environmental Change*, **19(2)**, 156-166.

Caldwell, T.M., A.F. Jorm, and K.B.G. Dear, 2004: Suicide and mental health in rural, remote and metropolitan areas in Australia. *Medical Journal of Australia*, **181(7 Suppl.)**, S10-S14.

Campbell, B., S. Mitchell, and M. Blackett, 2009: *Responding to Climate Change in Vietnam. Opportunities for Improving Gender Equality.* A Policy Discussion Paper, Oxfam and UN-Viet Nam, Ha noi, Vietnam, 62 pp.

Caplow, S., P. Jagger, K. Lawlor, and E. Sills, 2011: Evaluating land use and livelihood impacts of early forest carbon projects: lessons for learning about REDD+. *Environmental Science & Policy*, **14(2)**, 152-167.

Carr, E.R., 2008: Between structure and agency: livelihoods and adaptation in Ghana's Central Region. *Global Environmental Change*, **18(4)**, 689-699.

Carr, E.R., 2013: Livelihoods as intimate government: reframing the logic of livelihoods for development. *Third World Quarterly*, **34(1)**, 77-108.

Carter, M.R., P.D. Little, T. Mogues, and W. Negatu, 2007: Poverty traps and natural disasters in Ethiopia and Honduras. *World Development*, **35(5)**, 835-856.

Cashman, A., L. Nurse, and C. John, 2010: Climate change in the Caribbean: the water management implications. *The Journal of Environment & Development*, **19(1)**, 42-67.

Casillas, C.E. and D.M. Kammen, 2010: The energy-poverty-climate nexus. *Science*, **330(6008)**, 1181-1182.

Challinor, A., T. Wheeler, C. Garforth, P. Craufurd, and A. Kassam, 2007: Assessing the vulnerability of food crop systems in Africa to climate change. *Climatic Change*, **83(3)**, 381-399.

Chambers, R. and G. Conway, 1992: *Sustainable Rural Livelihoods: Practical Concepts for the 21st Century.* Institute of Development Studies (IDS), University of Sussex, Brighton, UK, 33 pp.

Chronic Poverty Research Centre, 2008: *The Chronic Poverty Report 2008-09: Escaping Poverty Traps.* Chronic Poverty Research Centre (CPRC), Belmont Press, Ltd., Northampton, UK, 148 pp.

Chu, J., 2011: Gender and 'land grabbing' in sub-Saharan Africa: women's land rights and customary land tenure. *Development*, **54(1)**, 35-39.

CIDA, 2002: *Gender Equality and Climate Change: Why Consider Gender Equality when taking Action on Climate Change?* Canadian International Development Agency (CIDA), Gatineau, QC, Canada, 3 pp.

Clot, N. and J. Carter, 2009: *Disaster Risk Reduction: A Gender and Livelihood Perspective.* InfoResources Focus No. 2/09, InfoResources operated by the Swiss institutions: Intercooperation (IC-HO), Info Service CDE and InfoAgrar / SHL, in partnership with IC India / Bangladesh / Mali / Andes, CETRAD (Kenya) and SIMAS (Nicaragua) and the Swiss Agency for Development and Cooperation (SDC), InfoResources, Zollikofen, Switzerland, 16 pp.

Collier, P., 2007: *The Bottom Billion. Why the Poorest Countries are Failing and What Can Be Done About It.* Oxford University Press, New York, NY, USA, 205 pp.

Collier, P., G. Conway, and T. Venables, 2008: Climate change and Africa. *Oxford Review of Economic Policy*, **24(2)**, 337-353.

Condon, N., H. Klemick, and A. Wolverton, 2013: *Impacts of Ethanol Policy on Corn Prices: A Review and Meta-Analysis of Recent Evidence.* Selected Paper prepared for presentation at the Agricultural & Applied Economics Association's 2013 AAEA & CAES Joint Annual Meeting, Washington, DC, August 4-6, 2013, 48 pp.

Confalonieri, U., B. Menne, R. Akhtar, K.L. Ebi, M. Hauengue, R.S. Kovats, B. Revich, and A.J. Woodward, 2007: Human health. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 391-431.

Conway, D. and E.L.F. Schipper, 2011: Adaptation to climate change in Africa: challenges and opportunities identified from Ethiopia. *Global Environmental Change*, **21(1)**, 227-237.

Corbera, E. and N. Jover, 2012: The undelivered promises of the Clean Development Mechanism: insights from three projects in Mexico. *Carbon*, **3(1)**, 39-54.

Cordona, O.D., M.K. van Aalst, J. Birkmann, M. Fordham, G. McGregor, R. Perez, R.S. Pulwarty, E.L.F. Schipper, and B.T. Sinh, 2012: Determinants of risk: exposure and vulnerability. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 65-108.

Cordova, R., M. Gelobter, A. Hoerner, J. Love, A. Miller, C. Saenger, and D. Zaidi, 2006: *Climate Change in California: Health, Economic and Equity Impacts.* Redefining Progress, Oakland, CA, USA, 109 pp.

Cotula, L., S. Vermeulen, R. Leonard, and J. Keeley, 2009: *Land Grab or Development Opportunity? Agricultural Investment and International Land Deals in Africa.* The International Institute for Environment and Development (IIED), London, UK, Food and Agriculture Organization of the United Nations (FAO), and the International Fund for Agricultural Development (IFAD), Rome, Italy, 120 pp.

Coulthard, S., 2008: Adapting to environmental change in artisanal fisheries – insights from a South Indian Lagoon. *Global Environmental Change*, **18(3)**, 479-489.

Cranfield, J.A.L., P.V. Preckel, and T.W. Hertel, 2007: *Poverty Analysis using an International Cross-Country Demand System.* Policy Research Working Paper 4285, the Trade Team, Development Research Group, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 49 pp.

Crate, S.A., 2013: *Climate Change and Human Mobility in Indigenous Communities of the Russian North.* Brookings-LSE Project on Internal Displacement, The Brookings Institution, Washington, DC, USA, 45 pp.

CRED, 2012: *The International Disaster Database.* UNDP, New York, NY, USA, pp. 1-8.

Crowe, T.L., 2013: The potential of the CDM to deliver pro-poor benefits. *Climate Policy*, **13(1)**, 58-79.

Cudjoe, G., C. Breisinger, and X. Diao, 2010: Local impacts of a global crisis: food price transmission, consumer welfare and poverty in Ghana. *Food Policy*, **35(4)**, 294-302.

Cutter, S., B. Osman-Elasha, J. Campbell, S.-M. Cheong, S. McCormick, R. Pulwarty, S. Supratid, and G. Ziervogel, 2012: Managing the risks from climate extremes at the local level. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 291-338.

D'Agostino, A.L. and B.K. Sovacool, 2011: Sewing climate-resilient seeds: implementing climate change adaptation best practices in rural Cambodia. *Mitigation and Adaptation Strategies for Global Change*, **16(6)**, 699-720.

Daley, E. and B. Englert, 2010: Securing land rights for women. *Journal of Eastern African Studies*, **4(1)**, 91-113.

Daniel, S., 2011: Land grabbing and potential implications for world food security. In: *Sustainable Agricultural Development* [Behnassi, M., S.A. Shahid, and J. D'Silva (eds.)]. Springer Science, Dordrecht, Netherlands, pp. 25-42.

Danielsen, F., M. Skutsch, N.D. Burgess, P.M. Jensen, H. Andrianandrasana, B. Karky, R. Lewis, J.C. Lovett, J. Massao, and Y. Ngaga, 2011: At the heart of REDD+: a role for local people in monitoring forests? *Conservation Letters*, **4(2)**, 158-167.

Dankelman, I., 2010: Introduction: exploring gender, environment, and climate change. In: *Gender and Climate Change: An Introduction* [Dankelman, I. (ed.)]. Earthscan, London, UK and Sterling, VA, USA, pp. 1-20.

Dauvergne, P. and K.J. Neville, 2009: The changing north-south and south-south political economy of biofuels. *Third World Quarterly*, **30(6)**, 1087-1102.

Davies, M., B. Guenther, J. Leavy, T. Mitchell, and T. Tanner, 2009: *Climate Change Adaptation, Disaster Risk Reduction and Social Protection: Complementary Roles in Agriculture and Rural Growth*? IDS Working Paper No. 320, The Institute of Development Studies (IDS), University of Sussex, Brighton, UK, 37 pp.

De Jode, H., 2010: *Modern and Mobile: The Future of Livestock Production in Africa's Drylands.* International Institute for Environment and Development (IIED), London, UK and SOS Sahel International UK, Oxford, UK, 88 pp.

De Schutter, O., 2011: How not to think of land-grabbing: three critiques of large-scale investments in farmland. *The Journal of Peasant Studies*, **38(2)**, 249-279.

de Sherbinin, A., M. Castro, F. Gemenne, M. Cernea, S. Adamo, P. Fearnside, G. Krieger, S. Lahmani, A. Oliver-Smith, and A. Pankhurst, 2011: Preparing for resettlement associated with climate change. *Science*, **334(6055)**, 456-457.

Deininger, K.W., D. Byerlee, J. Lindsay, A. Norton, H. Selod, and M. Stickler, 2011: *Rising Global Interest in Farmland: Can It Yield Sustainable and Equitable Benefits?* The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 214 pp.

Demetriades, J. and E. Esplen, 2008: The gender dimensions of poverty and climate change adaptation. *IDS Bulletin*, **39(4)**, 24-31.

Denton, F., 2002: Climate change vulnerability, impacts, and adaptation: why does gender matter? *Gender and Development*, **10(2)**, 10-20.

Dercon, S., 2006: Vulnerability: a micro perspective. In: *Securing Development in an Unstable World* [Bourguignon, F., B. Pleskovic, and J. van der Gaag (eds.)]. World Bank Publications, Washington, DC, USA, pp. 117-146.

Dercon, S., 2011: *Social Protection*, *Efficiency and Growth.* Paper prepared for The Annual Bank Conference on Development Economics (ABCDE), 2011, "Broadening Opportunities for Development," Paris, France, May 30-June 1, held by the OECD, the Government of France, and the World Bank, CSAE Working Paper WPS/2011-17, Centre for the Study of African Economies (CSAE), Department of Economics, University of Oxford, Oxford, UK, 29 pp.

Devereux, S., R. Sabates-Wheeler, M. Tefera, and H. Taye, 2006: *Ethiopia's Productive Safety Net Programme (PSNP): Trends in PSNP Transfers within Targeted Households.* Institute of Development Studies (IDS), University of Sussex, Brighton, UK and Indak International Pvt. L. C., Addis Ababa, Ethiopia, 68 pp.

Devereux, S., M. Davies, A. McCord, R. Slater, N. Freeland, F. Ellis, and P. White, 2010: *Social Protection in Africa: Where Next?* Institute of Development Studies (IDS), University of Sussex, Brighton, UK, 9 pp.

Devereux, S., J.A. McGregor, and R. Sabates-Wheeler, 2011: Introduction: social protection for social justice. *IDS Bulletin*, **42(6)**, 1-9.

Devitt, C. and R.S.J. Tol, 2012: Civil war, climate change, and development: a scenario study for sub-Saharan Africa. *Journal of Peace Research*, **49(1)**, 129-145.

Dollar, D., T. Kleineberg, and A. Kraay, 2013: *Growth Still is Good for the Poor.* Policy Research Working Paper No. 6568, The Macroeconomics and Growth Team, Development Research Group, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 33 pp.

Dossou, K.M.R. and B. Glehouenou-Dossou, 2007: The vulnerability to climate change of Cotonou (Benin): the rise in sea level. *Environment and Urbanization*, **19(1)**, 65-79.

Douglas, I., K. Alam, M.A. Maghenda, Y. Mcdonnell, L. McLean, and J. Campbell, 2008: Unjust waters: climate change, flooding and the urban poor in Africa. *Environment and Urbanization*, **20(1)**, 187-205.

Dunne, J.P., R.J. Stouffer, and J.G. John, 2013: Reductions in labour capacity from heat stress under climate warming. *Nature Climate Change*, **3**, 563-566, doi:10.1038/nclimate1827.

Dyer, J.C., L.C. Stringer, and A.J. Dougill, 2012: *Jatropha curcas*: Sowing local seeds of success in Malawi? In response to Achten et al. (2010). *Journal of Arid Environments*, **79**, 107-110.

Eakin, H., K. Benessaiah, J.F. Barrera, G.M. Cruz-Bello, and H. Morales, 2012: Livelihoods and landscapes at the threshold of change: disaster and resilience in a Chiapas coffee community. *Regional Environmental Change*, **12(3)**, 475-488.

Eakin, H.C. and M.B. Wehbe, 2009: Linking local vulnerability to system sustainability in a resilience framework: two cases from Latin America. *Climatic Change*, **93(3)**, 355-377.

Easterling, W.E., P.K. Aggarwal, P. Batima, K.M. Brander, L. Erda, S.M. Howden, A. Kirilenko, J. Morton, J. Schmidhuber, and F.N. Tubiello, 2007: Food, fibre and forest

products. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge, Cambridge, UK and New York, NY, USA, pp. 273-313.

Eastham, J., F. Mpelasoka, M. Mainuddin, C. Ticehurst, P. Dyce, G. Hodgson, R. Ali, and M. Kirby, 2008: *Mekong River Basin Water Resources Assessment: Impacts of Climate Change.* Water for a Healthy Country National Research Flagship Report Series, The Commonwealth Scientific and Industrial Research Organisation (CSIRO), Canberra, Australia, 131 pp.

Edenhofer, O., R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, and S. Schlömer (eds.), 2011: *The IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Prepared by Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1075 pp.

Edward, P. and A. Sumner, 2013a: *The Future of Global Poverty in a Multi-Speed World: New Estimates of Scale and Location, 2010-2030.* CGD Working Paper No. 327, Centre for Global Development (CGD), Washington, DC, USA, 42 pp.

Edward, P. and A. Sumner, 2013b: *The Geography of Inequality. Where and by How Much Has Income Distribution Changed since 1990?* CGD Working Paper 341, Centre for Global Development (CGD), Washington, DC, USA, 42 pp.

Elbers, C., J.W. Gunning, and B. Kinsey, 2007: Growth and risk: methodology and micro evidence. *World Bank Economic Review*, **21(1)**, 1-20.

Elliott, J.R. and J. Pais, 2006: Race, class, and Hurricane Katrina: social differences in human responses to disaster. *Social Science Research*, **35(2)**, 295-321.

Ellis, F. and S. Biggs, 2001: Evolving themes in rural development 1950s-2000s. *Development Policy Review*, **19(4)**, 437-448.

Ellis, F., M. Kutengule, and A. Nyasulu, 2003: Livelihoods and rural poverty reduction in Malawi. *World Development*, **31(9)**, 1495-1510.

Elobeid, A. and C. Hart, 2008: Ethanol expansion in the Food versus Fuel Debate: how will developing countries fare? *Journal of Agricultural & Food Industrial Organization*, **5(SI)**, 6, www.energybc.ca/cache/biofuels/finaledits/www.colby.edu/economics/faculty/thtieten/ec476/Ethanol_LDCs.pdf.

El-Raey, M., K. Dewidar, and M. El-Hattab, 1999: Adaptation to the impacts of sea level rise in Egypt. *Mitigation and Adaptation Strategies for Global Change*, **4(3)**, 343-361.

Eriksen, C., N. Gill, and L. Head, 2010: The gendered dimensions of bushfire in changing rural landscapes in Australia. *Journal of Rural Studies*, **26(4)**, 332-342.

Eriksen, S. and J. Lind, 2009: Adaptation as a political process: adjusting to drought and conflict in Kenya's drylands. *Environmental Management*, **43(5)**, 817-835.

Eriksen, S. and A. Marin, 2011: *Pastoral Pathways. Climate Change Adaptation Lessons from Ethiopia.* Department of International Environment and Development Studies, Noragric Norwegian University of Life Sciences, the Development Fund/Utviklingsfond, Oslo, Norway, 51 pp.

Eriksen, S. and K. O'Brien, 2007: Vulnerability, poverty and the need for sustainable adaptation measures. *Climate Policy*, **7(4)**, 337-352.

Eriksen, S. and J.A. Silva, 2009: The vulnerability context of a savanna area in Mozambique: household drought coping strategies and responses to economic change. *Environmental Science & Policy*, **12(1)**, 33-52.

Eriksen, S., P. Aldunce, C. Bahinipati, Sekhar, M., D. Rafael, J. Molefe, C. Nhemachena, K. O'Brien, F. Olorunfemi, J. Park, L. Sygna, and K. Ulsrud, 2011: When not every response to climate change is a good one: identifying principles for sustainable adaptation. *Climate and Development*, **3(1)**, 7-20.

Estrada, M. and E. Corbera, 2012: The potential of carbon offsetting projects in the forestry sector for poverty reduction in developing countries: the application of ecology in development solutions. In: *Integrating Ecology and Poverty Reduction* [Carter Ingram, J., F. DeClerck, and C. Rumbaitis del Rio (eds.)]. Springer, New York, NY, USA, pp. 137-147.

Fankhauser, S. and G. Schmidt-Traub, 2011: From adaptation to climate-resilient development: the costs of climate-proofing the Millennium Development Goals in Africa. *Climate and Development*, **3(2)**, 94-113.

Fashae, O.A. and O.D. Onafeso, 2011: Impact of climate change on sea level rise in Lagos, Nigeria. *International Journal of Remote Sensing*, **32(24)**, 9811-9819.

Ferreira, V.R.S. and C.S. Passador, 2011: Potentials and limits to generate employment and income by the National Programme for Production and Use of Biodiesel. *Organizações Rurais & Agroindustriais*, **12(1)**, 20-33.

Field, C.B., L.D. Mortsch, M. Brklacich, D.L. Forbes, P. Kovacs, S.W. Running, and M.J. Scott, 2007: North America. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 617-652.

Fisher, M., M. Chaudhury, and B. McCusker, 2010: Do forests help rural households adapt to climate variability? Evidence from Southern Malawi. *World Development*, **38(9)**, 1241-1250.

Ford, J.D., 2009: Vulnerability of Inuit food systems to food insecurity as a consequence of climate change: a case study from Igloolik, Nunavut. *Regional Environmental Change*, **9(2)**, 83-100.

Fordham, M., S. Gupta, S. Akerkar, and M. Scharf, 2011: *Leading Resilient Development: Grassroots Women's Priorities, Practices and Innovations.* Grassroots Organizations Operating Together in Sisterhood (GROOTS) International, Northumbia University, School of the Built and Natural Environment, and the United Nations Development Programme (UNDP), UNDP, New York, NY, USA, and GROOTS International, Brooklyn, NY, USA, 76 pp.

Fortin, E., 2011: *Multi-Stakeholder Initiatives to Regulate Biofuels: The Roundtable for Sustainable Biofuels.* Paper presented at the International Conference on Global Land Grabbing, 6-8 April 2011, organized by the Land Deal Politics Initiative (LDPI), International Institute of Social Studies in The Hague, and Erasmus University Rotterdam, in collaboration with the Journal of Peasant Studies, hosted by the Future Agricultures Consortium at the Institute of Development Studies (IDS), University of Sussex, Brighton, UK, LDPI, The Hague, Netherlands, 15 pp.

Frumkin, H., J. Hess, G. Luber, J. Malilay, and M. McGeehin, 2008: Climate change: the public health response. *American Journal of Public Health*, **98(3)**, 435-445.

Funk, C., M.D. Dettinger, J.C. Michaelsen, J.P. Verdin, M.E. Brown, M. Barlow, and A. Hoell, 2008: Warming of the Indian Ocean threatens eastern and southern African food security but could be mitigated by agricultural development. *Proceedings of the National Academy of Sciences of the United States of America*, **105(32)**, 11081-11086.

Fussell, E., N. Sastry, and M. VanLandingham, 2010: Race, socioeconomic status, and return migration to New Orleans after Hurricane Katrina. *Population & Environment*, **31(1)**, 20-42.

Gabrielsson, S. and V. Ramasar, 2012: Widows: agents of change in a climate of water uncertainty. *Journal of Cleaner Production*, 1 December 2013, **60**, 34-42.

Gabrielsson, S., S. Brogaard, and A. Jerneck, 2012: Living without buffers – illustrating climate vulnerability in the Lake Victoria basin. *Sustainability Science*, **8(2)**, 143-157, doi:10.1007/s11625-012-0191-3.

Gagnon-Lebrun, F. and S. Agrawala, 2006: *Progress on Adaptation to Climate Change in Developed Countries: An Analysis of Broad Trends.* Organisation for Economic Co-operation and Development (OECD), Paris, France, 62 pp.

Gaiha, R. and A.B. Deolalikar, 1993: Persistent, expected and innate poverty: estimates for semi-arid rural South India, 1975-1984. *Cambridge Journal of Economics*, **17(4)**, 409-421.

Galaz, V., F. Moberg, T.E. Downing, F. Thomalla, and K. Warner, 2008: *Ecosystem under Pressure.* A Policy Brief for the International Commission on Climate Change and Development (CCCD), Prepared by the Stockholm Resilience Centre, Stockholm University, Stockholm Environment Institute (SEI), and United Nations University-Institute for Environment and Human Security (UNU-EHS), CCCD, Stockholm, Sweden, 4 pp.

García-Pina, R., A. Tobías Garcés, J. Sanz Navarro, C. Navarro Sánchez, and A. García-Fulgueiras, 2008: Efecto del calor sobre el número de urgencias hospitalarias en la Región de Murcia durante los veranos del período 2000-2005 y su uso en la vigilancia epidemiológica. *Revista Española de Salud Pública*, **82(2)**, 153-166.

Gasper, D.R., A.V. Portocarrero, and A. Lera St Clair, 2013: Climate change and development framings: a comparative analysis of the Human Development Report 2007/8 and the World Development Report 2010. *Global Environmental Change*, **23(1)**, 28-39.

Gentle, P. and T.N. Maraseni, 2012: Climate change, poverty and livelihoods: adaptation practices by rural mountain communities in Nepal. *Environmental Science & Policy*, **21**, 24-34.

Gerlitz, J., K. Hunzai, and B. Hoermann, 2012: Mountain poverty in the Hindu-Kush Himalayas. *Canadian Journal of Development Studies/Revue Canadienne D'Études du Développement*, **33(2)**, 250-265.

Ghazoul, J., R.A. Butler, J. Mateo-Vega, and L.P. Koh, 2010: REDD: a reckoning of environment and development implications. *Trends in Ecology & Evolution*, **25(7)**, 396-402.

Ghosh, J., 2010: The unnatural coupling: food and global finance. *Journal of Agrarian Change*, **10(1)**, 72-86.

Gigli, S. and S. Agrawala, 2007: *Stocktaking of Progress on Integrating Adaptation to Climate Change into Development Co-operation Activities.* Organisation for Economic Co-operation and Development (OECD), Paris, France, 83 pp.

Gilligan, D.O., J. Hoddinott, and A.S. Taffesse, 2009: The impact of Ethiopia's Productive Safety Net Programme and its linkages. *The Journal of Development Studies*, **45(10)**, 1684-1706.

Giné, X. and D. Yang, 2009: Insurance, credit, and technology adoption: field experimental evidence from Malawi. *Journal of Development Economics*, **89(1)**, 1-11.

Giné, X., R. Townsend, and J. Vickery, 2008: Patterns of rainfall insurance participation in rural India. *The World Bank Economic Review*, **22(3)**, 539-566.

Glenna, L. and D.R. Cahoy, 2009: Agribusiness concentration, intellectual property, and the prospects for rural economic benefits from the emerging biofuel economy. *Southern Rural Sociology*, **24(2)**, 111-129.

Goh, A.H.X., 2012: *A Literature Review of the Gender-Differentiated Impacts of Climate Change on Women's and Men's Assets and Well-Being in Developing Countries.* CAPRi Working Paper No. 106, CGIAR Systemwide Program on Collective Action and Property Rights (CAPRi) and the International Food Policy Research Institute (IFPRI), Washington, DC, USA, 38 pp.

Gong, Y., 2010: *Integrating Social Capital into Institutional Analysis of the Guangxi CDM Forest-based Carbon Sequestration Project.* Economy and Environment Program for Southeast Asia Project (EEPSEA), International Development Research Centre (IDRC), Singapore, 23 pp.

Gopinathan, M.C. and R. Sudhakaran, 2011: Biofuels: opportunities and challenges in India. In: *Biofuels: Global Impact on Renewable Energy, Production Agriculture, and Technological Advancements* [Tomes, D., P. Lakshmanan, and D. Songstad (eds.)]. Springer, New York, NY, USA, pp. 173-209.

Gough, I., 2010: Economic crisis, climate change and the future of welfare states. *Twenty-First Century Society*, **5(1)**, 51-64.

Green, D., L. Alexander, K. McInnes, J. Church, N. Nicholls, and N. White, 2010: An assessment of climate change impacts and adaptation for the Torres Strait Islands, Australia. *Climatic Change*, **102(3)**, 405-433.

Gupta, A., E. Lövbrand, E. Turnhout, and M.J. Vijge, 2012: In pursuit of carbon accountability: the politics of REDD+ measuring, reporting and verification systems. *Current Opinion in Environmental Sustainability*, **4(6)**, 726-731.

Hahn, G., 1997: Dynamic responses of cattle to thermal heat loads. *Journal of Animal Science*, **77**, 10-20.

Hall, J., S. Matos, L. Severino, and N. Beltrão, 2009: Brazilian biofuels and social exclusion: established and concentrated ethanol versus emerging and dispersed biodiesel. *Journal of Cleaner Production*, **17(Suppl. 1)**, S77-S85.

Halstead, P. and J. O'Shea, 2004: *Bad Year Economics: Cultural Responses to Risk and Uncertainty.* Cambridge University Press, Cambridge, UK and New York, NY, USA, 160 pp.

Hanff, E., M. Dabat, and J. Blin, 2011: Are biofuels an efficient technology for generating sustainable development in oil-dependent African nations? A macroeconomic assessment of the opportunities and impacts in Burkina Faso. *Renewable and Sustainable Energy Reviews*, **15(5)**, 2199-2209.

Hardoy, J. and G. Pandiella, 2009: Urban poverty and vulnerability to climate change in Latin America. *Environment and Urbanization*, **21(1)**, 203-224.

Hardoy, J., G. Pandiella, and L.S.V. Barrero, 2011: Local disaster risk reduction in Latin American urban areas. *Environment and Urbanization*, **23(2)**, 401-413.

Hargreaves, D., 2013: Gender and climate change: implications for responding to the needs of those affected by natural disasters and other severe weather events. In: *Research, Action and Policy: Addressing the Gendered Impacts of Climate Change* [Alston, M. and K. Whittenbury (eds.)]. Springer, Dordrecht, Netherlands, pp. 277-281.

Hassan, R. and C. Nhemachena, 2008: Determinants of African farmers' strategies for adapting to climate change: multinomial choice analysis. *African Journal of Agricultural and Resource Economics*, **2(1)**, 83-104.

Hayes, T. and L. Persha, 2010: Nesting local forestry initiatives: revisiting community forest management in a REDD+ world. *Forest Policy and Economics*, **12(8)**, 545-553.

Hazeleger, T., 2013: Gender and disaster recovery: strategic issues and action in Australia. *Australian Journal of Emergency Management*, **28(2)**, 40-46.

Heckenberg, D. and I. Johnston, 2012: Climate change, gender and natural disasters: social differences and environment-related victimisation. In: *Climate Change from a Criminological Perspective* [White, R. (ed.)]. Springer Science, Dordrecht, Netherlands, pp. 149-171.

Hellmuth, M.E., A. Moorhead, M.C. Thomson, and J. Williams (eds.), 2007: *Climate Risk Management in Africa: Learning from Practice.* Climate and Society Series No. 1, International Research Institute for Climate and Society (IRI), The Earth Institute at Columbia University, Lamont Campus, Palisades, NY, USA, 104 pp.

Heltberg, R., P.B. Siegel, and S.L. Jorgensen, 2009: Addressing human vulnerability to climate change: toward a 'no-regrets' approach. *Global Environmental Change*, **19(1)**, 89-99.

Hertel, T.W. and S.D. Rosch, 2010: Climate change, agriculture, and poverty. *Applied Economic Perspectives and Policy*, **32(3)**, 355-385.

Hertel, T.W., M.B. Burke, and D.B. Lobell, 2010: The poverty implications of climate-induced crop yield changes by 2030. *Global Environmental Change*, **20(4)**, 577-585.

Hett, C., A. Heinimann, M.I. Epprecht, P. Messerli, and K. Hurni, 2012: Carbon pools and poverty peaks in Lao PDR: spatial data inform policy-making for REDD+ at the national level. *Mountain Research and Development*, **32(4)**, 390-399, doi:10.1659/MRD-JOURNAL-D-12-00065.1.

Hewitt, K. and M. Mehta, 2012: Rethinking risk and disasters in mountain areas. *Revue De Géographie Alpine/Journal of Alpine Research*, **100(1)**, doi:10.4000/rga.1653.

Hochrainer-Stigler, S., R.B. Sharma, and R. Mechler, 2012: Disaster microinsurance for pro-poor risk management: evidence from South Asia. *Journal of Integrated Disaster Risk Management*, **2(2)**, doi:10.5595/idrim.2012.0033.

Hollander, G., 2010: Power is sweet: sugarcane in the global ethanol assemblage. *The Journal of Peasant Studies*, **37(4)**, 699-721.

Homewood, K., 2009: *Ecology of African Pastoralist Societies.* James Currey, Ltd., Oxford, UK, 320 pp.

Hope, K.R., 2009: Climate change and poverty in Africa. *International Journal of Sustainable Development & World Ecology*, **16(6)**, 451-461.

Horton, G., L. Hanna, and B. Kelly, 2010: Drought, drying and climate change: emerging health issues for ageing Australians in rural areas. *Australasian Journal on Ageing*, **29(1)**, 2-7.

Houghton, R., 2009: 'Everything became a struggle, absolute struggle': post- flood increases in domestic violence in New Zealand. In: *Women, Gender and Disaster: Global Issues and Initiatives* [Enarson, E. and P.G.D. Chakrabarti (eds.)]. Vivek Mehra for Sage Publications India Pvt Ltd., New Delhi, India, pp. 99-111.

Howden, S.M., J.F. Soussana, F.N. Tubiello, N. Chhetri, M. Dunlop, and H. Meinke, 2007: Adapting agriculture to climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **104(50)**, 19691-19696.

Huang, C., A.G. Barnett, X. Wang, P. Vaneckova, G. FitzGerald, and S. Tong, 2011: Projecting future heat-related mortality under climate change scenarios: a systematic review. *Environmental Health Perspectives*, **119(12)**, 1681-1690.

Hulme, D. and A. Shepherd, 2003: Conceptualizing chronic poverty. *World Development*, **31(3)**, 403-423.

Huq, S., F. Yamin, A. Rahman, A. Chatterjee, X. Yang, S. Wade, V. Orindi, and J. Chigwada, 2005: Linking climate adaptation and development: a synthesis of six case studies from Asia and Africa. *IDS Bulletin*, **36(4)**, 117-122.

IEG, 2012: *Adapting to Climate Change: Assessing the World Bank Group Experience Phase III.* Independent Evaluation Group of the World Bank (IEG), Washington, DC, USA, 149 pp.

IFAD, 2011: *Rural Poverty Report 2011. New Realities, New Challenges: New Opportunities for Tomorrow's Generation.* International Fund for Agricultural Development (IFAD), Rome, Italy, 319 pp.

IFRC, 2010: *World Disasters Report 2010: Focus on Urban Risk.* International Federation of Red Cross and Red Crescent Societies (IFRC), Geneva, Switzerland, 214 pp.

Iglesias, A., S. Quiroga, and A. Diz, 2011: Looking into the future of agriculture in a changing climate. *European Review of Agricultural Economics*, **38(3)**, 427-447.

IPCC, 2007: *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K and A. Reisinger (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

IPCC, 2012a: Summary for Policymakers. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 19 pp.

IPCC, 2012b: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker,

D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp.

Iwasaki, S., B.H.N. Razafindrabe, and R. Shaw, 2009: Fishery livelihoods and adaptation to climate change: a case study of Chilika lagoon, India. *Mitigation and Adaptation Strategies for Global Change*, **14(4)**, 339-355.

Jabeen, H., C. Johnson, and A. Allen, 2010: Built-in resilience: learning from grassroots coping strategies for climate variability. *Environment and Urbanization*, **22(2)**, 415-431.

Jacoby, H., M. Rabassa, and E. Skoufias, 2011: *Distributional Implications of Climate Change in India.* Policy Research Working Paper 5623, the Poverty Reduction and Equity Unit, Poverty Reduction and Economic Management Network, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 53 pp.

Jalan, J. and M. Ravallion, 1998: Transient poverty in postreform rural China. *Journal of Comparative Economics*, **26(2)**, 338-357.

Jalan, J. and M. Ravallion, 2000: Is transient poverty different? Evidence for rural China. *The Journal of Development Studies*, **36(6)**, 82-99.

Jankowska, M., D. Lopez-Carr, C. Funk, G. Husak, and Z. Chafe, 2012: Climate change and human health: spatial modeling of water availability, malnutrition, and livelihoods in Mali, Africa. *Applied Geography*, **33**, 4-15.

Jarosz, L., 2012: Growing inequality: agricultural revolutions and the political ecology of rural development. *International Journal of Agricultural Sustainability*, **10(2)**, 192-199.

Jenkins, P. and B. Phillips, 2008: Battered women, catastrophe, and the context of safety after Hurricane Katrina. *NWSA Journal*, **20(3)**, 49-68.

Jerneck, A. and L. Olsson, 2012: A smoke-free kitchen: initiating community based co-production for cleaner cooking and cuts in carbon emissions. *Journal of Cleaner Production*, **60**, 208-215, doi:10.1016/j.jclepro.2012.09.026.

Jindal, R., 2010: Livelihood impacts of payments for forest carbon services: field evidence from Mozambique. In: *Payments for Environmental Services, Forest Conservation and Climate Change: Livelihoods in the REDD?* [Tacconi, L., S. Mahanty, and H. Suich (eds.)]. Edward Elgar, Cheltenham, UK and Northampton, MA, USA, pp. 185-211.

Jindal, R., B. Swallow, and J. Kerr, 2008: Forestry-based carbon sequestration projects in Africa: potential benefits and challenges. *Natural Resources Forum*, **32(2)**, 116-130.

Jones, P.G. and P.K. Thornton, 2009: Croppers to livestock keepers: livelihood transitions to 2050 in Africa due to climate change. *Environmental Science & Policy*, **12(4)**, 427-437.

Julia and B. White, 2012: Gendered experiences of dispossession: oil palm expansion in a Dayak Hibun community in West Kalimantan. *Journal of Peasant Studies*, **39(3-4)**, 995-1016.

Kabubo-Mariara, J., 2008: Climate change adaptation and livestock activity choices in Kenya: an economic analysis. *Natural Resources Forum*, **32(2)**, 131-141.

Kaijser, A. and A. Kronsell, 2013: Climate change through the lens of intersectionality. *Environmental Politics*, _, 1-17, doi:10.1080/09644016.2013.835203.

Kakota, T., D. Nyariki, D. Mkwambisi, and W. Kogi-Makau, 2011: Gender vulnerability to climate variability and household food insecurity. *Climate and Development*, **3(4)**, 298-309.

Kanowski, P.J., C.L. McDermott, and B.W. Cashore, 2011: Implementing REDD+: lessons from analysis of forest governance. *Environmental Science & Policy*, **14(2)**, 111-117.

Karambiri, H., S. García Galiano, J. Giraldo, H. Yacouba, B. Ibrahim, B. Barbier, and J. Polcher, 2011: Assessing the impact of climate variability and climate change on runoff in West Africa: the case of Senegal and Nakambe River basins. *Atmospheric Science Letters*, **12(1)**, 109-115.

Karavai, M. and M. Hinostroza, 2013: Conceptualizations of sustainability in carbon markets. *Climate and Development*, **5(1)**, doi:10.1080/17565529.2012.762332.

Karlan, D., R.D. Osei, I. Osei-Akoto, and C. Udry, 2012: *Agricultural Decisions after Relaxing Credit and Risk Constraints*. NBER Working Paper No. 18463, National Bureau of Economic Research (NBER), Cambridge, MA, USA, 64 pp.

Karver, J., C. Kenny, and A. Sumner, 2012: *MDGs 2.0: What Goals, Targets, and Timeframe?* CGD Working Paper 297, Center for Global Development (CGD), Washington, DC, USA, 60 pp.

Kates, R.W., 2000: Cautionary tales: adaptation and the global poor. *Climatic Change*, **45(1)**, 5-17.

Kaygusuz, K., 2011: Energy services and energy poverty for sustainable rural development. *Renewable and Sustainable Energy Reviews*, **15(2)**, 936-947.

Kaygusuz, K., 2012: Energy for sustainable development: a case of developing countries. *Renewable and Sustainable Energy Reviews*, **16(2)**, 1116-1126.

Keshavarz, M., E. Karami, and F. Vanclay, 2013: The social experience of drought in rural Iran. *Land Use Policy*, **30(1)**, 120-129.

Klein, R.J.T., E.L.F. Schipper, and S. Dessai, 2005: Integrating mitigation and adaptation into climate and development policy: three research questions. *Environmental Science & Policy*, **8(6)**, 579-588.

Kovats, R.S. and S. Hajat, 2008: Heat stress and public health: a critical review. *Annual Review of Public Health*, **29**, 41-55.

Krause, T. and L. Loft, 2013: Benefit distribution and equity in Ecuador's Socio Bosque Program. *Society and Natural Resources*, **26(10)**, 1170-1184, doi:10.1080/08941920.2013.797529.

Kumar, S., A. Chaube, and S.K. Jain, 2011: Critical review of jatropha biodiesel promotion policies in India. *Energy Policy*, February 2012, **41**, 775-781.

Kurukulasuriya, P. and R. Mendelsohn, 2007: *Crop Selection: Adapting to Climate Change in Africa.* Policy Research Working Paper No. 4307, the Sustainable Rural and Urban Development Team, Development Research Group, The International Bank for Reconstruction and Development / The World Bank, Washington DC, USA, 27 pp.

Lacombe, G., M. McCartney, and G. Forkuor, 2012: Drying climate in Ghana over the period 1960-2005: evidence from the resampling-based Mann-Kendall test at local and regional levels. *Hydrological Sciences Journal*, **57(8)**, 1594-1609.

Laderach, P., M. Lundy, A. Jarvis, J. Ramirez, E.P. Portilla, K. Schepp, and A. Eitzinger, 2011: Predicted impact of climate change on coffee supply chains. *Climate Change Management*, **(4)**, 703-723.

Laderchi, C.R., R. Saith, and F. Stewart, 2003: Does it matter that we do not agree on the definition of poverty? A comparison of four approaches. *Oxford Development Studies*, **31(3)**, 243-274.

Lambrou, Y. and S. Nelson, 2013: Gender issues in climate change adaptation: farmers' food security in Andhra Pradesh. In: *Research, Action and Policy: Addressing the Gendered Impacts of Climate Change* [Alston, M. and K. Whittenbury (eds.)]. Springer Science, Dordrecht, Netherland, pp. 189-206.

Lambrou, Y. and G. Paina, 2006: *Gender: The Missing Component of the Response to Climate Change.* Gender and Population Division, Sustainable Development Department, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 44 pp.

Larson, A.M., 2011: Forest tenure reform in the age of climate change: lessons for REDD+. *Global Environmental Change*, **21(2)**, 540-549.

Le Blanc, D., W. Liu, O'Conner, D. D., and I. Zubcevic, 2012: *Issue 1: Development Cooperation in the Light of Sustainable Development and the SDGs: Preliminary Explorations of the Issues.* Rio+20 Working Papers, United Nations Division of Sustainable Development, United Nations Department of Economic and Social Affairs (UNDESA), New York, NY, USA, 23 pp.

Leach, M., R. Mearns, and I. Scoones, 1999: Environmental entitlements: dynamics and institutions in community-based natural resource management. *World Development*, **27(2)**, 225-247.

Leary, N., J. Adejuwon, V. Barros, I. Burton, J. Kulkarni, and R. Lasco (eds.), 2008: *Climate Change and Adaptation.* Earthscan, London, UK and Sterling, VA, USA, 376 pp.

Leichenko, R.M. and K.L. O'Brien, 2008: *Environmental Change and Globalization: Double Exposures.* Oxford University Press, New York, NY, USA, 192 pp.

Lemos, M.C., E. Boyd, E.L. Tompkins, H. Osbahr, and D. Liverman, 2007: Developing adaptation and adapting development. *Ecology and Society*, **12(2)**, 26, www.ecologyandsociety.org/vol12/iss2/art26/.

Li, Y., D. Conway, Y. Wu, Q. Gao, S. Rothausen, W. Xiong, H. Ju, and E. Lin, 2013: Rural livelihoods and climate variability in Ningxia, Northwest China. *Climatic Change*, **119(3-4)**, 1-14.

Linnerooth-Bayer, J. and R. Mechler, 2006: Insurance for assisting adaptation to climate change in developing countries: a proposed strategy. *Climate Policy*, **6(6)**, 621-636.

Little, P.D., M.P. Stone, T. Mogues, A.P. Castro, and W. Negatu, 2006: 'Moving in place': drought and poverty dynamics in South Wollo, Ethiopia. *The Journal of Development Studies*, **42(2)**, 200-225.

Little, P.D., J. McPeak, C.B. Barrett, and P. Kristjanson, 2008: Challenging orthodoxies: understanding poverty in pastoral areas of East Africa. *Development and Change*, **39(4)**, 587-611.

Liu, J., S. Fritz, C. Van Wesenbeeck, M. Fuchs, L. You, M. Obersteiner, and H. Yang, 2008: A spatially explicit assessment of current and future hotspots of hunger in Sub-Saharan Africa in the context of global change. *Global and Planetary Change*, **64(3-4)**, 222-235.

Liverman, D.M., 2009: Conventions of climate change: constructions of danger and the dispossession of the atmosphere. *Journal of Historical Geography*, **35(2)**, 279-296.

Lobell, D.B., M.B. Burke, C. Tebaldi, M.D. Mastrandrea, W.P. Falcon, and R.L. Naylor, 2008: Prioritizing climate change adaptation needs for food security in 2030. *Science*, **319(5863)**, 607-610.

Lohmann, L., 2010: Uncertainty markets and carbon markets: variations on Polanyian themes. *New Political Economy*, **15(2)**, 225-254.

Lund, E., 2010: Dysfunctional delegation: why the design of the CDM's supervisory system is fundamentally flawed. *Climate Policy*, **10(3)**, 277-288.

Lynn, K., K. MacKendrick, and E.M. Donoghue, 2011: *Social Vulnerability and Climate Change: Synthesis of Literature.* General Technical Report PNW-GTR-838, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Washington, DC, USA, 70 pp.

MacGregor, S., 2010: 'Gender and climate change': from impacts to discourses. *Journal of the Indian Ocean Region*, **6(2)**, 223-238.

MacKerron, G.J., C. Egerton, C. Gaskell, A. Parpia, and S. Mourato, 2009: Willingness to pay for carbon offset certification and co-benefits among (high-)flying young adults in the UK. *Energy Policy*, **37(4)**, 1372-1381.

MacLennan, M. and L. Perch, 2012: Environmental justice in Latin America and the Caribbean: legal empowerment of the poor in the context of climate change. *Climate Law*, **3(3)**, 283-309.

Mader, T.L., 2012: Heat Stress-contributing factors, effects and management. In: *Proceedings of the Plains Council Spring Conference 2012, San Antonio, Texas, 12-13 April, 2012*. Publication No. AREC 2012-26, Texas Agrilife Research and Extension Center, The Texas A&M System, Amarillo, Texas, USA, pp. 22-27.

Mahanty, S., H. Suich, and L. Tacconi, 2012: Access and benefits in payments for environmental services and implications for REDD+: lessons from seven PES schemes. *Land Use Policy*, March 2013**, 31**, 38-47.

Mahul, O., N. Belete, and A. Goodland, 2009: *Index-based Livestock Insurance in Mongolia.* Focus 17, Brief 9, International Food Policy Research Institute (IFPRI), Washington, DC, USA, 2 pp.

Manik, Y., J. Leahy, and A. Halog, 2013: Social life cycle assessment of palm oil biodiesel: a case study in Jambi Province of Indonesia. *The International Journal of Life Cycle Assessment*, **18(7)**, 1386-1392.

Manzo, K., 2010: Imaging vulnerability: the iconography of climate change. *Area*, **42(1)**, 96-107.

Mapfumo, P., F. Mtambanengwe, and R. Chikowo, 2010: *Mobilizing Local Safety Nets for Enhanced Adaptive Capacity to Climate Change and Variability in Zimbabwe.* Adaptation Insights November 2010. No 1, Lack of Resilience in African Smallholder Farming: Exploring Measures to Enhance the Adaptive Capacity of Local Communities to Pressures of Climate Change" Project, supported by the Climate Change Adaptation in Africa (CCAA) program, a joint initiative of Canada's International Development Research Centre (IDRC) and the United Kingdom's Department for International Development (DFID), IDRC, Ottawa, ON, Canada, 4 pp.

Matsaert, H., J. Kariuki, and A. Mude, 2011: Index-based livestock insurance for Kenyan pastoralists: an innovation systems perspective. *Development in Practice*, **21(3)**, 343-356.

McCright, A.M. and R.E. Dunlap, 2000: Challenging global warming as a social problem: an analysis of the conservative movement's counter-claims. *Social Problems*, **47(4)**, 499-522.

McDermott, C.L., K. Levin, and B. Cashore, 2011: Building the forest-climate bandwagon: REDD+ and the logic of problem amelioration. *Global Environmental Politics*, **11(3)**, 85-103.

McDowell, J. and J. Hess, 2012: Accessing adaptation: multiple stressors on livelihoods in the Bolivian highlands under a changing climate. *Global Environmental Change*, **22(2)**, 342-352.

McGranahan, G., D. Balk, and B. Anderson, 2007: The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization*, **19(1)**, 17-37.

McGregor, G., M. Cox, Y. Cui, Z. Cui, M. Davey, R. Graham, and A. Brookshaw, 2006: Winter-season climate prediction for the UK health sector. *Journal of Applied Meteorology and Climatology*, **45(12)**, 1782-1792.

McLaughlin, P. and T. Dietz, 2008: Structure, agency and environment: toward an integrated perspective on vulnerability. *Global Environmental Change*, **18(1)**, 99-111.

McLeman, R. and B. Smit, 2006: Migration as an adaptation to climate change. *Climatic Change*, **76(1)**, 31-53.

McSweeney, K. and O.T. Coomes, 2011: Climate-related disaster opens a window of opportunity for rural poor in northeastern Honduras. *Proceedings of the National Academy of Sciences of the United States of America*, **108(13)**, 5203-5208.

Mearns, R. and A. Norton, 2010: *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World.* New Frontiers of Social Policy 52097, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 319 pp.

Mechler, R., J. Linnerooth-Bayer, and D. Peppiatt, 2006: *Microinsurance for Natural Disaster Risks in Developing Countries.* ProVention Consortium, Geneva, Switzerland, in collaboration with the International Institute of Applied Systems Analysis (IIASA), Laxenburg, Austria, 31 pp.

Meenawat, H. and B.K. Sovacool, 2011: Improving adaptive capacity and resilience in Bhutan. *Mitigation and Adaptation Strategies for Global Change*, **16(5)**, 515-533.

Melamed, C., 2012: *After 2015: Contexts, Politics and Processes for a Post-2015 Global Agreement on Development.* Overseas Development Institute (ODI), London, UK, 63 pp.

Mendelsohn, R., A. Dinar, and L. Williams, 2006: The distributional impact of climate change on rich and poor countries. *Environment and Development Economics*, **11(02)**, 159-178.

Menon, N., 2009: Rainfall uncertainty and occupational choice in agricultural households of rural Nepal. *The Journal of Development Studies*, **45(6)**, 864-888.

Mertz, O., K. Halsnæs, J.E. Olesen, and K. Rasmussen, 2009: Adaptation to climate change in developing countries. *Environmental Management*, **43(5)**, 743-752.

Michaelowa, A., 2011: Failures of global carbon markets and CDM? *Climate Policy*, **11(1)**, 839-841.

Michaelowa, A. and K. Michaelowa, 2011: Climate business for poverty reduction? The role of the World Bank. *The Review of International Organizations*, **6(3)**, 259-286.

Michaelowa, A., J. Buen, and A. Michaelowa, 2012: The CDM gold rush. In: *Carbon Markets or Climate Finance* [Michaelowa, J. and A. Michaelowa (eds.)]. Routledge, Abingdon, UK and New York, NY, USA, pp. 1-38.

Midgley, G.F. and W. Thuiller, 2011: Potential responses of terrestrial biodiversity in Southern Africa to anthropogenic climate change. *Regional Environmental Change*, **11**, 127-135.

Milanovic, B., 2012: Global inequality recalculated and updated: the effect of new PPP estimates on global inequality and 2005 estimates. *Journal of Economic Inequality*, **10(1)**, 1-18.

Minang, P.A., M.K. McCall, and H.T.A. Bressers, 2007: Community capacity for implementing Clean Development Mechanism projects within community forests in Cameroon. *Environmental Management*, **39(5)**, 615-630.

Misselhorn, A.A., 2005: What drives food insecurity in southern Africa? A meta-analysis of household economy studies. *Global Environmental Change Part A*, **15(1)**, 33-43.

Mitchell, D., 2008: *A Note on Rising Food Prices.* Policy Research Working Paper 4682, The World Bank Development Prospects Group, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 20 pp.

Mitlin, D. and D. Satterthwaite, 2013: *Urban Poverty in the Global South: Scale and Nature.* Routledge, Abingdon, UK and New York, NY, USA, 354 pp.

Mittelman, J.H., 2013: Global *Bricolage*: emerging market powers and polycentric governance. *Third World Quarterly*, **34(1)**, 23-37.

Mol, A.P.J., 2010: Environmental authorities and biofuel controversies. *Environmental Politics*, **19(1)**, 61-79.

Mol, A.P.J., 2012: Carbon flows, financial markets and climate change mitigation. *Environmental Development*, **1(1)**, 10-24.

Molony, T., 2011: Bioenergy policies in Africa: mainstreaming gender amid an increasing focus on biofuels. *Biofuels, Bioproducts and Biorefining*, **5(3)**, 330-341.

Montefrio, M.J.F., 2012: Privileged biofuels, marginalized indigenous peoples: the coevolution of biofuels development in the tropics. *Bulletin of Science, Technology & Society*, **32(1)**, 41-55.

Montefrio, M.J.F. and D.A. Sonnenfeld, 2013: Global-local tensions in contract farming of biofuel crops involving indigenous communities in the Philippines. *Society & Natural Resources*, **26(3)**, 239-253.

Morello-Frosch, R., M. Pastor, J. Sadd, and S. Shonkoff, 2009: *The Climate Gap: Inequalities in How Climate Change Hurts Americans & How to Close the Gap.* USC Dornsife, College of Letters, Arts and Sciences, Program for Environmental and Regional Equity (PERE), University of Southern California, Los Angeles, CA, USA, 31 pp.

Morton, J.F., 2007: The impact of climate change on smallholder and subsistence agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, **104(50)**, 19680-19685.

Mosse, D., 2010: A relational approach to durable poverty, inequality and power. *The Journal of Development Studies*, **46(7)**, 1156-1178.

Müller, C., W. Cramer, W.L. Hare, and H. Lotze-Campen, 2011: Climate change risks for African agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, **108(11)**, 4313-4315.

Murray, C., 2002: Livelihoods research: transcending boundaries of time and space. *Journal of Southern African Studies*, **28(3)**, 489-509.

Mustalahti, I., A. Bolin, E. Boyd, and J. Paavola, 2012: Can REDD+ reconcile local priorities and needs with global mitigation benefits? Lessons from Angai Forest, Tanzania. *Ecology and Society*, **17(1)**, 16, www.ecologyandsociety.org/vol17/iss1/art16/.

Muthoni, J.W. and E.E. Wangui, 2013: Women and climate change: strategies for adaptive capacity in Mwanga District, Tanzania. *African Geographical Review*, **32(1)**, 59-71.

Neelormi, S., N. Adri, and A. Uddin Ahmed, 2008: *Gender Perspectives of Increased Socio-Economic Risks of Waterlogging in Bangladesh due to Climate Change.* International Ocean Institute, St. Petersburg, FL, USA, 11 pp.

Nellemann, C., R. Verma, and L. Hislop, 2011: *Women at the Frontline of Climate Change: Gender Risks and Hopes: A Rapid Response Assessment.* United Nations Environment Programme (UNEP) and GRID-Arendal, Arendal, Norway, 66 pp.

Nelson, V. and T. Stathers, 2009: Resilience, power, culture, and climate: a case study from semi-arid Tanzania, and new research directions. *Gender & Development*, **17(1)**, 81-94.

Nesamvuni, E., R. Lekalakala, D. Norris, and J. Ngambi, 2012: Effects of climate change on dairy cattle, South Africa. *African Journal of Agricultural Research*, **7(26)**, 3867-3872.

Neumayer, E. and T. Plümper, 2007: The gendered nature of natural disasters: the impact of catastrophic events on the gender gap in life expectancy, 1981-2002. *Annals of the Association of American Geographers*, **97(3)**, 551-566.

Neupane, S. and K. Shrestha, 2012: Sustainable forest governance in a changing climate: impacts of REDD program on the livelihood of poor communities in Nepalese community forestry. *OIDA International Journal of Sustainable Development*, **4(1)**, 71-82.

Neville, K.J. and P. Dauvergne, 2012: Biofuels and the politics of mapmaking. *Political Geography*, **31(5)**, 279-289.

New, M., D. Liverman, H. Schroder, and K. Anderson, 2011: Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications. *Philosophical Transactions of the Royal Society A*, **369(1934)**, 6-19.

Newell, P. and A. Bumpus, 2012: The global political ecology of the Clean Development Mechanism. *Global Environmental Politics*, **12(4)**, 49-67.

Nightingale, A., 2009: Warming up the climate change debate: a challenge to policy based on adaptation. *Journal of Forest and Livelihood*, **8(1)**, 84-89.

Nightingale, A., 2011: Bounding difference: Intersectionality and the material production of gender, caste, class and environment in Nepal. *Geoforum*, **42(2)**, 153-162.

Niño-Zarazúa, M., 2011: *Mexico's Progresa-Oportunidades and the emergence of social assistance in Latin America.* BWPI Working Paper No. 142, Brooks World Poverty Institute (BWPI), University of Manchester, Manchester, UK, 24 pp.

Nkem, J., R. Munang, and B.P. Jallow, 2011: *Lessons for Adaptation in sub-Saharan Africa.* Climate change Adaptation & Development Programme (CC Dare), jointly implemented by the United Nations Environment Programme (UNEP) and United Nations Development Programme (UNDP), Nairobi, Kenya, 85 pp.

Nkem, J.N., O.A. Somorin, C. Jum, M.E. Idinoba, Y.M. Bele, and D.J. Sonwa, 2012: Profiling climate change vulnerability of forest indigenous communities in the Congo Basin. *Mitigation and Adaptation Strategies for Global Change*, **18(5)**, 513-533.

Nordhaus, W.D., 2010: Economic aspects of global warming in a post-Copenhagen environment. *Proceedings of the National Academy of Sciences of the United States of America*, **107(26)**, 11721-11726.

Nussbaum, M.C., 2001: *Women and Human Development: The Capabilities Approach.* Cambridge University Press, Cambridge, UK and New York, NY, USA, 312 pp.

Nussbaum, M.C., 2011: *Creating Capabilities: The Human Development Approach.* Belknap Press, a division of Harvard University Press, Cambridge, MA, USA, 237 pp.

Obidzinski, K., R. Andriani, H. Komanidin, and A. Andrianto, 2012: Environmental and social impacts of oil palm plantations and their implications for biofuel production in Indonesia. *Ecology and Society*, **17(1)**, 25, www.ecologyandsociety.org/vol17/iss1/art25/.

O'Brien, G., P. O'Keefe, H. Meena, J. Rose, and L. Wilson, 2008: Climate adaptation from a poverty perspective. *Climate Policy*, **8(2)**, 194-201.

O'Brien, K., 2012: Global environmental change II: from adaptation to deliberate transformation. *Progress in Human Geography*, **36(5)**, 667-676.

O'Brien, K.L. and R.M. Leichenko, 2000: Double exposure: assessing the impacts of climate change within the context of economic globalization. *Global Environmental Change*, **10(3)**, 221-232.

O'Brien, K.L. and R.M. Leichenko, 2003: Winners and losers in the context of global change. *Annals of the Association of American Geographers*, **93(1)**, 89-103.

O'Brien, K., A.L. St Clair, and B. Kristoffersen, 2010: *Climate Change, Ethics and Human Security.* Cambridge University Press, Cambridge, UK and New York, NY, USA, 231 pp.

O'Brien, K., M. Pelling, A. Patwardhan, S. Hallegatte, A. Maskrey, T. Oki, U. Oswald-Spring, T. Wilbanks, and P.Z. Yanda, 2012: Toward a sustainable and resilient future. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 437-486.

O'Connor, A., 2002: *Poverty Knowledge: Social Science, Social Policy, and the Poor in Twentieth-Century US History.* Princeton University Press, Princeton, NJ, USA, 373 pp.

OECD, 2011: *Divided We Stand: Why Inequality Keeps Rising.* Organisation for Economic Co-operation and Development (OECD), Paris, France, 388 pp.

O'Laughlin, B., 2002: Proletarianisation, agency and changing rural livelihoods: forced labour and resistance in colonial Mozambique. *Journal of Southern African Studies*, **28(3)**, 511-530.

Olsen, K.H., 2007: The clean development mechanism's contribution to sustainable development: a review of the literature. *Climatic Change*, **84(1)**, 59-73.

Onta, N. and B.P. Resurreccion, 2011: The Role of gender and caste in climate adaptation strategies in Nepal. *Mountain Research and Development*, **31(4)**, 351-356.

O'Reilly, C.M., S.R. Alin, P.D. Plisnier, A.S. Cohen, and B.A. McKee, 2003: Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa. *Nature*, **424(6950)**, 766-768.

Orlove, B., 2009: The past, the present and some possible futures of adaptation. In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, N., I. Lorenzoni, and K. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK, pp. 131-163.

Orr, Y., R. Schimmer, R. Geerken, A. Castro, D. Taylor, and D. Brokensha, 2012: Ethnoecology in the shadow of rain and the light of experience: local perceptions of drought and climate change in east Sumba, Indonesia. In: *Climate Change and Threatened Communities* [Castro, A.P., D. Taylor, and D.W. Brokensha (eds.)]. Practical Action Publishing, Rugby, UK, pp. 175-184.

Ortiz, I. and M. Cummins, 2011: *Global Inequality: Beyond the Bottom Billion: A Rapid Review of Income Distribution in 141 Countries.* UNICEF Social and Economic Policy Working Paper, United Nations International Emergency Children's Fund (UNICEF), New York, NY, USA, 65 pp.

Ortiz, I. and M. Cummins, 2013: *The Age of Austerity: A Review of Public Expenditures and Adjustment Measures in 181 Countries.* Working Paper March 2013, Initiative for Policy Dialogue, New York, NY, USA and the South Centre, Geneva, Switzerland, 55 pp.

Osbahr, H., C. Twyman, W. Neil Adger, and D.S.G. Thomas, 2008: Effective livelihood adaptation to climate change disturbance: scale dimensions of practice in Mozambique. *Geoforum*, **39(6)**, 1951-1964.

Osbahr, H., C. Twyman, W.N. Adger, and D.S.G. Thomas, 2010: Evaluating successful livelihood adaptation to climate variability and change in southern Africa. *Ecology and Society*, **15(2)**, 27, www.ecologyandsociety.org/vol15/iss2/art27/.

Ostfeld, R.S., 2009: Climate change and the distribution and intensity of infectious diseases. *Ecology*, **90(4)**, 903-905.

Ostrom, E., 2010: Polycentric systems for coping with collective action and global environmental change. *Global Environmental Change*, **20(4)**, 550-557.

Paavola, J., 2008: Livelihoods, vulnerability and adaptation to climate change in Morogoro, Tanzania. *Environmental Science & Policy*, **11(7)**, 642-654.

Paavola, J. and W.N. Adger, 2006: Fair adaptation to climate change. *Ecological Economics*, **56(4)**, 594-609.

Pagán Motta, M., 2013: *Detecting Vulnerable Groups in DHHS ASPR's EMR Data during Response: A Snapshot of Superstorm Sandy*. Proceedings of 141st APHA Annual Meeting, November 2-6, 2013, Boston, MA, USA, apha.confex.com/apha/141am/webprogramadapt/Paper282601.html.

Parikh, P., S. Chaturvedi, and G. George, 2012: Empowering change: the effects of energy provision on individual aspirations in slum communities. *Energy Policy*, November 2012, **50**, 477-485.

Parkinson, D., C. Lancaster, and A. Stewart, 2011: A numbers game: lack of gendered data impedes prevention of disaster-related family violence. *Health Promotion Journal of Australia*, **22**, 42-45.

Parks, B.C. and J.T. Roberts, 2010: Climate change, social theory and justice. *Theory, Culture & Society*, **27(2-3)**, 134-166.

Patricola, C.M. and K.H. Cook, 2010: Northern African climate at the end of the twenty-first century: an integrated application of regional and global climate models. *Climate Dynamics*, **35(1)**, 193-212.

Patt, A., P. Suarez, and U. Hess, 2010: How do small-holder farmers understand insurance, and how much do they want it? Evidence from Africa. *Global Environmental Change*, **20(1)**, 153-161.

Patz, J.A., D. Campbell-Lendrum, T. Holloway, and J.A. Foley, 2005: Impact of regional climate change on human health. *Nature*, **438**, 310-317.

Peach Brown, H., 2011: Gender, climate change and REDD+ in the Congo Basin forests of Central Africa. *International Forestry Review*, **13(2)**, 163-176.

Pelling, M., 2010: *Adaptation to Climate Change: From Resilience to Transformation.* Routledge, Abingdon, UK and New York, NY, USA, 203 pp.

Peralta, A., 2008: *Gender and Climate Change Finance: A Case Study from the Philippines.* The Women's Environment and Development Organization (WEDO), New York, NY, USA, 19 pp.

Peraza, S., C. Wesseling, A. Aragon, R. Leiva, R.A. García-Trabanino, C. Torres, K. Jakobsson, C.G. Elinder, and C. Hogstedt, 2012: Decreased kidney function among agricultural workers in El Salvador. *American Journal of Kidney Diseases*, **59(4)**, 531-540.

Perch, L., 2011: *Mitigation of What and by What? Adaptation by Whom and for Whom? Dilemmas in Delivering for the Poor and the Vulnerable in International Climate Policy.* Working Paper 79, United Nations Development Programme (UNDP) and International Policy Centre for Inclusive Growth (IPC-IG), IPC-IG, Brasilia, Brazil, 51 pp.

Perch, L. and R. Roy, 2010: *Social Policy in the Post-Crisis Context of Small Island Developing States: A Synthesis.* United Nations Development Programme (UNDP) and International Policy Centre for Inclusive Growth (IPC-IG), Brasilia, IPC-IG, Brasilia, Brazil, 56 pp.

Perch, L., C. Watson, and B. Barry, 2012: *Resource Inequality: Moving Inequalities from the Periphery to the Centre of the Post-2015 Agenda.* Background Paper for "Addressing Inequalities" Global Thematic Consultation, published online by the Addressing Inequalities Networked Alliance (AINA), a joint Civil Society/UN consultation, co-led by the United Nations International Emergency Children's Fund (UNICEF) and the United Nations Entity for Gender Equality and the Empowerment of Women (UN WOMEN) with support from the Governments of Denmark and Ghana, UNICEF, New York, NY, USA, 25 pp.

Pereira, R.B. and R. Pereira, 2008: Population health needs beyond ratifying the Kyoto Protocol: occupational deprivation. *Rural and Remote Health*, **8(927)**, 1-5.

Peskett, L., 2007: *Biofuels, Agriculture and Poverty Reduction.* Natural Resources Perspectives No. 107, Overseas Development Institute (ODI), London, UK, 6 pp.

Peters, P.E., 2013: Conflicts over land and threats to customary tenure in Africa. *African Affairs*, **112(449)**, 543-562.

Peters-Stanley, M. and K. Hamilton, 2012: *Developing Dimension: State of the Voluntary Carbon Markets 2012.* Forest Trends Association, Washington, DC, USA, 110 pp.

Petheram, L., K. Zander, B. Campbell, C. High, and N. Stacey, 2010: 'Strange changes': indigenous perspectives of climate change and adaptation in NE Arnhem Land (Australia). *Global Environmental Change*, **20(4)**, 681-692.

Petrie, B., 2010: *Gender and Climate Change: Regional Report: Executive Summary.* Heinrich B□ll Foundation, Cape Town, South Africa, 4 pp.

Phelps, J., E.L. Webb, and A. Agrawal, 2010: Does REDD+ threaten to recentralize forest governance? *Science*, **328(5976)**, 312-313.

Piao, S., P. Ciais, Y. Huang, Z. Shen, S. Peng, J. Li, L. Zhou, H. Liu, Y. Ma, and Y. Ding, 2010: The impacts of climate change on water resources and agriculture in China. *Nature*, **467(7311)**, 43-51.

Pielke Jr, R., G. Prins, S. Rayner, and D. Sarewitz, 2007: Lifting the taboo on adaptation. *Nature*, **445**, 597-598.

Pierro, R. and B. Desai, 2008: Climate insurance for the poor: challenges for targeting and participation. *IDS Bulletin*, **39(4)**, 123-129.

Pogge, T.W., 2009: *Politics as Usual: What Lies Behind the Pro-Poor Rhetoric.* Polity Press, Cambridge, UK and Malden, MA, USA, 224 pp.

Pokorny, B., I. Scholz, and W. de Jong, 2013: REDD+ for the poor or the poor for REDD+? About the limitations of environmental policies in the Amazon and the potential of achieving environmental goals through pro-poor policies. *Ecology and Society*, **18(2)**, 3, www.ecologyandsociety.org/vol18/iss2/art3/.

Polain, J.D., H.L. Berry, and J.O. Hoskin, 2011: Rapid change, climate adversity and the next 'big dry': older farmers' mental health. *Australian Journal of Rural Health*, **19(5)**, 239-243.

Posey, J., 2009: The determinants of vulnerability and adaptive capacity at the municipal level: evidence from floodplain management programs in the United States. *Global Environmental Change*, **19(4)**, 482-493.

Pouliotte, J., B. Smit, and L. Westerhoff, 2009: Adaptation and development: livelihoods and climate change in Subarnabad, Bangladesh. *Climate and Development*, **1(1)**, 31-46.

Pradhan, E.K., K.P. West Jr, J. Katz, S.C. LeClerq, S.K. Khatry, and S.R. Shrestha, 2007: Risk of flood-related mortality in Nepal. *Disasters*, **31(1)**, 57-70.

Quinn, C.H., G. Ziervogel, A. Taylor, T. Takama, and F. Thomalla, 2011: Coping with multiple stresses in rural South Africa. *Ecology and Society*, **16(3)**, 2, www.ecologyandsociety.org/vol16/iss3/art2/.

Quisumbing, A.R., N. Kumar, and J. Behrman, 2011: *Do Shocks Affect Men's and Women's Assets Differently? A Review of Literature and New Evidence from Bangladesh and Uganda.* International Food Policy Research Institute (IFPRI), Washington, DC, USA, 48 pp.

Rahlao, S., B. Mantlana, H. Winkler, and T. Knowles, 2012: South Africa's national REDD+ initiative: assessing the potential of the forestry sector on climate change mitigation. *Environmental Science & Policy*, **17**, 24-32.

Rahman, M., 2013: Climate change, disaster and gender vulnerability: a study on two divisions of Bangladesh. *American Journal of Human Ecology*, **2(2)**, 72-82.

Ravallion, M. and S. Chen, 2012: Monitoring inequality. In: *Let's Talk Development.* A blog hosted by the World Bank's Chief Economist, submitted on June 20, 2012, The World Bank, Washington, DC, USA, blogs.worldbank.org/developmenttalk/monitoring-inequality.

Ray-Bennett, N.S., 2009: Multiple disasters and policy responses in pre-and post-independence Orissa, India. *Disasters*, **33(2)**, 274-290.

Reason, J., 2000: Human error: models and management. *BMJ: British Medical Journal*, **320(7237)**, 768.

Reed, M.S., G. Podesta, I. Fazey, N. Geeson, R. Hessel, K. Hubacek, D. Letson, D. Nainggolan, C. Prell, and M.G. Rickenbach, 2013: Combining analytical frameworks to assess livelihood vulnerability to climate change and analyse adaptation options. *Ecological Economics*, **94**, 66-77.

Reid, P. and C. Vogel, 2006: Living and responding to multiple stressors in South Africa – glimpses from KwaZulu-Natal. *Global Environmental Change*, **16(2)**, 195-206.

Renton, A., 2009: *Suffering the Science: Climate Change, People, and Poverty.* Oxfam Briefing Paper No. 130, Oxfam International, Boston, MA, USA, 61pp.

Resurreccion, B.P., 2011: *The Gender and Climate Debate: More of the Same or New Pathways of Thinking and Doing?* Asia Security Initiative Policy Series, Working Paper No. 10, RSIS Centre for Non-Traditional Security (NTS) Studies, Singapore, 19 pp.

Ribot, J., 2010: Vulnerability does not fall from the sky: toward multiscale, pro-poor climate policy. In: *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World* [Mearns, R. and A. Norton (eds.)]. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, pp. 47-74.

Roberts, J.T., 2011: Multipolarity and the new world (dis)order: US hegemonic decline and the fragmentation of the global climate regime. *Global Environmental Change*, **21(3)**, 776-784.

Robertson, B. and P. Pinstrup-Andersen, 2010: Global land acquisition: neo-colonialism or development opportunity? *Food Security*, **2(3)**, 271-283.

Rodima-Taylor, D., 2011: Social innovation and climate adaptation: local collective action in diversifying Tanzania. *Applied Geography*, **33**, 128-134.

Röhr, U., 2006: Gender and climate change. *Tiempo*, **59**, 3-7.

Rosset, P., 2011: Food sovereignty and alternative paradigms to confront land grabbing and the food and climate crises. *Development*, **54(1)**, 21-30.

Ruel, M.T., J.L. Garrett, C. Hawkes, and M.J. Cohen, 2010: The food, fuel, and financial crises affect the urban and rural poor disproportionately: a review of the evidence. *The Journal of Nutrition*, **140(Suppl. 1)**, 170S-176S.

Rulli, M.C., A. Saviori, and P. D'Odorico, 2013: Global land and water grabbing. *Proceedings of the National Academy of Sciences of the United States of America*, **110(3)**, 892-897.

Runge, C.F. and B. Senauer, 2007: How biofuels could starve the poor. *Foreign Affairs*, **86(3)**, www.foreignaffairs.com/articles/62609/c-ford-runge-and-benjamin-senauer/how-biofuels-could-starve-the-poor.

Sabates-Wheeler, R., T. Mitchell, and F. Ellis, 2008: Avoiding repetition: time for CBA to engage with the livelihoods literature? *IDS Bulletin*, **39(4)**, 53-59.

Sachs, J., 2006: *The End of Poverty: Economic Possibilities for Our Time.* Penguin Group, New York, NY, USA, 397 pp.

Saito, Y., 2009: Gender mainstreaming into community-based disaster management in the context of regional development. *Regional Development Dialogue*, **30(1)**, 37-46.

Salack, S., B. Muller, A.T. Gaye, F. Hourdin, and N. Cisse, 2012: Multi-scale analyses of dry spells across Niger and Senegal. *Science et changements planétaires/Sécheresse*, **23(1)**, 3-13.

Sallu, S.M., C. Twyman, and L.C. Stringer, 2010: Resilient or vulnerable livelihoods? Assessing livelihood dynamics and trajectories in rural Botswana. *Ecology and Society*, **15(4)**, 3, www.ecologyandsociety.org/vol15/iss4/art3/.

Satterthwaite, D., 2011: How can urban centers adapt to climate change with ineffective or unrepresentative local governments? *Wiley Interdisciplinary Reviews: Climate Change*, **2(5)**, 767-776.

Satterthwaite, D. and D. Mitlin, 2013: *Reducing Urban Poverty in the Global South.* Routledge, Abingdon, UK and New York, NY, USA, pp. 301.

Savaresi, A., 2013: REDD+ and human rights: addressing synergies between international regimes. *Ecology and Society*, **18(3)**, 5, www.ecologyandsociety.org/vol18/iss3/art5/.

Schipper, E.L.F., 2007: *Climate Change Adaptation and Development: Exploring the Linkages.* Working Paper No. 107, Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, and South East Asia START Regional Centre, Tyndall Centre for Climate Change Research, Norwich, UK, 13 pp.

Schipper, L. and M. Pelling, 2006: Disaster risk, climate change and international development: scope for, and challenges to, integration. *Disasters*, **30(1)**, 19-38.

Schlenker, W. and D.B. Lobell, 2010: Robust negative impacts of climate change on African agriculture. *Environmental Research Letters*, **5**, 014010, doi:10.1088/1748-9326/5/1/014010.

Schmidhuber, J. and F.N. Tubiello, 2007: Climate change and food security special feature: global food security under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **104(50)**, 19703-19708.

Schwartz, J., 2007: A billion dollars later, New Orleans still at risk. *The New York Times*, **August 17, 2007**, www.nytimes.com/2007/08/17/us/nationalspecial/17protect.html?pagewanted=all&_r=0.

Scoones, I., 1998: *Sustainable Rural Livelihoods: A Framework for Analysis*. IDS Working Paper No. 72, Institute of Development Studies (IDS), University of Sussex, Brighton, UK, 22 pp.

Scoones, I., 2009: Livelihoods perspectives and rural development. *The Journal of Peasant Studies*, **36(1)**, 171-196.

Scott-Joseph, A., 2010: Financing recovery: implications of natural disaster expenditure on the fiscal sustainability of the Eastern Caribbean Currency Unit (ECCU) States. *Journal of Business, Finance and Economics in Emerging Economies*, **5(2)**, 38-80.

Semenza, J.C., J.E. McCullough, W.D. Flanders, M.A. McGeehin, and J.R. Lumpkin, 1999: Excess hospital admissions during the July 1995 heat wave in Chicago. *American Journal of Preventive Medicine*, **16(4)**, 269-277.

Sen, A.K., 1976: Poverty: an ordinal approach to measurement. *Econometrica: Journal of the Econometric Society*, **44(2)**, 219-231.

Sen, A.K., 1981: Ingredients of famine analysis: availability and entitlements. *The Quarterly Journal of Economics*, **96(3)**, 433-464.

Sen, A.K., 1985: *Commodities and Capabilities.* Oxford University Press, Oxford, UK, 104 pp.

Sen, A.K., 1999: *Development as Freedom.* Oxford University Press, Oxford, UK, 384 pp.

Seo, S.N., 2010: Is an integrated farm more resilient against climate change? A micro-econometric analysis of portfolio diversification in African agriculture. *Food Policy*, **35(1)**, 32-40.

Seo, S.N., R. Mendelsohn, A. Dinar, R. Hassan, and P. Kurukulasuriya, 2009: A Ricardian analysis of the distribution of climate change impacts on agriculture across agro-ecological zones in Africa. *Environmental and Resource Economics*, **43(3)**, 313-332.

Shackleton, C.M., S.E. Shackleton, E. Buiten, and N. Bird, 2007: The importance of dry woodlands and forests in rural livelihoods and poverty alleviation in South Africa. *Forest Policy and Economics*, **9(5)**, 558-577.

Shah, K.U., H.B. Dulal, C. Johnson, and A. Baptiste, 2013: Understanding livelihood vulnerability to climate change: applying the livelihood vulnerability index in Trinidad and Tobago. *Geoforum*, **47**, 125-137.

Shankland, A. and L. Hasenclever, 2011: Indigenous peoples and the regulation of REDD+ in Brazil: beyond the War of the Worlds? *IDS Bulletin*, **42(3)**, 80-88.

Sherman, A. and I. Shapiro, 2005: *Essential Facts about the Victims of Hurricane Katrina.* Center on Budget and Policy Priorities, Washington, DC, USA, 3 pp.

Sherwood, S.C. and M. Huber, 2010: An adaptability limit to climate change due to heat stress. *Proceedings of the National Academy of Sciences of the United States of America*, **107(21)**, 9552-9555.

Shin, S., 2010: The domestic side of the clean development mechanism: the case of China. *Environmental Politics*, **19(2)**, 237-254.

Shonkoff, S., R. Morello-Frosch, M. Pastor, and J. Sadd, 2011: The climate gap: environmental health and equity implications of climate change and mitigation policies in California – a review of the literature. *Climatic Change*, **109(1)**, 485-503.

Sietz, D., M. Lüdeke, and C. Walther, 2011: Categorisation of typical vulnerability patterns in global drylands. *Global Environmental Change*, **21(2)**, 431-440.

Sietz, D., S.E. Mamani Choque, and M.K.B. Lüdeke, 2012: Typical patterns of smallholder vulnerability to weather extremes with regard to food security in the Peruvian Altiplano. *Regional Environmental Change*, **12(3)**, 489-505.

Silalertruksa, T., S.H. Gheewala, K. Hünecke, and U.R. Fritsche, 2012: Biofuels and employment effects: implications for socio-economic development in Thailand. *Biomass and Bioenergy*, November 2012, **46**, 409-418.

Sissoko, K., H. van Keulen, J. Verhagen, V. Tekken, and A. Battaglini, 2011: Agriculture, livelihoods and climate change in the West African Sahel. *Regional Environmental Change*, **11**, 119-125.

Skoufias, E., B. Essama-Nssah, and R.S. Katayama, 2011a: *Too Little Too Late: Welfare Impacts of Rainfall Shocks in Rural Indonesia.* Policy Research Working Paper No. 5615, the Poverty Reduction and Equity Unit, Poverty Reduction and Economic Management Network, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 20 pp.

Skoufias, E., M. Rabassa, S. Olivieri, and M. Brahmbhatt, 2011b: *The Poverty Impacts of Climate Change*. Economic Premise Note Series No. 51, Poverty Reduction and Economic Management (PREM) Network of the World Bank, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 5 pp., siteresources.worldbank.org/EXTPREMNET/Resources/EP51_v4.pdf.

Skoufias, E., K. Vinha, and H. Conroy, 2011c: *The Impacts of Climate Variability on Welfare in Rural Mexico.* Policy Research Working Paper 5555, the Poverty Reduction and Equity Unit, Poverty Reduction and Economic Management Network, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 59 pp.

Slater, R., J. Farrington, and R. and Holmes, 2006: *Linking Agricultural Growth and Social Protection: Inception Report*. Overseas Development Institute (ODI), London, UK, 30 pp.

Slater, R., L. Peskett, E. Ludi, and D. Brown, 2007: *Climate Change, Agricultural Policy and Poverty Reduction – How Much Do We Know?* Natural Resource Perspectives Series No. 109, Overseas Development Institute (ODI), with support from the Swedish International Development Cooperation Agency (Sida), ODI, London, UK, 6 pp.

Small, L.A., 2007: The sustainable rural livelihoods approach: a critical review. *Canadian Journal of Development Studies/Revue Canadienne D'Études du Développement*, **28(1)**, 27-38.

Smit, B. and M.W. Skinner, 2002: Adaptation options in agriculture to climate change: a typology. *Mitigation and Adaptation Strategies for Global Change*, **7(1)**, 85-114.

Smith, B., I. Burton, R.J.T. Klein, and J. Wandel, 2000: An anatomy of adaptation to climate change and variability. *Climatic Change*, **45(1)**, 223-251.

Smithers, J. and A. Blay-Palmer, 2001: Technology innovation as a strategy for climate adaptation in agriculture. *Applied Geography*, **21(2)**, 175-197.

Solomon, S., G.-K. Plattner, R. Knutti, and P. Friedlingstein, 2009: Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences of the United States of America*, **106(6)**, 1704-1709, doi: 10.1073/pnas.0812721106.

Somorin, O.A., I.J. Visseren-Hamakers, B. Arts, D.J. Sonwa, and A.M. Tiani, 2013: REDD+ policy strategy in Cameroon: actors, institutions and governance. *Environmental Science & Policy*, doi:10.1016/j.envsci.2013.02.004.

Son, J., J. Lee, G.B. Anderson, and M.L. Bell, 2012: The impact of heat waves on mortality in seven major cities in Korea. *Environmental Health Perspectives*, **120(4)**, 566-571.

Sowers, J., A. Vengosh, and E. Weinthal, 2011: Climate change, water resources, and the politics of adaptation in the Middle East and North Africa. *Climatic Change*, **104(3)**, 599-627.

Springate-Baginski, O. and E. Wollenberg, 2010: *REDD, Forest Governance and Rural Livelihoods: The Emerging Agenda.* The Center for International Forestry Research (CIFOR), Bogor, Indonesia, 279 pp.

St. Clair, A.L. and V. Lawson, 2013: From poverty to prosperity: Addressing growth, equity and ethics in a changing environment. In: *A Changing Environment for Human Security: Transformative Approaches to Research, Policy and Action* [Sygna, L., K. O'Brien, and J. Wolf (eds.)]. Routledge, Abingdon, UK and New York, NY, USA, pp. 203-215.

Stern, N., 2009: *Managing Climate Change and Overcoming Poverty: Facing the Realities and Building a Global Agreement.* Centre for Climate Change Economics and Policy (CCCEP) and the Grantham Research Institute on Climate Change and the Environment, London, UK, 28 pp.

Stringer, L.C., C. Twyman, and D.S.G. Thomas, 2007: Learning to reduce degradation on Swaziland's arable land: enhancing understandings of *Striga asiatica*. *Land Degradation and Development*, **18(2)**, 163-177.

Stringer, L.C., J.C. Dyer, M.S. Reed, A.J. Dougill, C. Twyman, and D. Mkwambisi, 2009: Adaptations to climate change, drought and desertification: local insights to enhance policy in southern Africa. *Environmental Science & Policy*, **12(7)**, 748-765.

Stringer, L.C., A.J. Dougill, D.D. Mkwambisi, J.C. Dyer, F.K. Kalaba, and M. Mngoli, 2012: Challenges and opportunities for carbon management in Malawi and Zambia. *Carbon*, **3(2)**, 159-173.

Subbarao, S. and B. Lloyd, 2011: Can the clean development mechanism (CDM) deliver? *Energy Policy*, **39(3)**, 1600-1611.

Sudmeier-Rieux, K., J.C. Gaillard, S. Sharma, J. Dubois, and M. Jaboyedoff, 2012: Floods, landslides, and adapting to climate change in Nepal: what role for climate change models? In: *Climate Change Modeling For Local Adaptation in the Hindu Kush-Himalayan Region* [Lamadrid, A. and I. Kelman (eds.)]. Community, Environment and Disaster Risk Management, Vol. 11, Emerald Group Publishing, Ltd., Bingley, UK, pp. 119-140.

Sulser, T.B., B. Nestorova, M.W. Rosegrant, and T. van Rheenen, 2011: The future role of agriculture in the Arab region's food security. *Food Security*, **3**, 23-48.

Sumner, A., 2010: *Global Poverty and the New Bottom Billion: What if Three-Quarters of the World's Poor Live in Middle-Income Countries?* Institute of Development Studies (IDS), University of Sussex, Brighton, UK, 42 pp.

Sumner, A., 2012a: Where do the poor live? *World Development*, **40(5)**, 865-877.

Sumner, A., 2012b: *Where Will the World's Poor Live? An Update on Global Poverty and the New Bottom Billion.* CGD working Paper No. 305, Center for Global Development (CGD), Washington, DC, USA, 33 pp.

Sumner, A., A. Suryahadi, and N. Thang, 2012: *Poverty and Inequalities in Middle-Income Southeast Asia.* Institute of Development Studies (IDS), University of Sussex, Brighton, UK, 20 pp.

Sutter, C. and J.C. Parreño, 2007: Does the current Clean Development Mechanism (CDM) deliver its sustainable development claim? An analysis of officially registered CDM projects. *Climatic Change*, **84(1)**, 75-90.

Swallow, B. and R. Meinzen-Dick, 2009: Payment for environmental services: interactions with property rights and collective action. In: *Institutions and Sustainability: Political Economy of Agriculture and the Environment.* [Beckmann, V. and M. Padmanabhan (eds.)]. Springer Science, Dordrecht, Netherlands, pp. 243-265.

Syvitski, J.P.M., A.J. Kettner, I. Overeem, E.W.H. Hutton, M.T. Hannon, G.R. Brakenridge, J. Day, C. Vörösmarty, Y. Saito, and L. Giosan, 2009: Sinking deltas due to human activities. *Nature Geoscience*, **2(10)**, 681-686.

Tacoli, C., 2009: Crisis or adaptation? Migration and climate change in a context of high mobility. *Environment and Urbanization*, **21(2)**, 513-525.

Tadesse, M. and M.V. Brans, 2012: Risk, coping mechanisms, and factors in the demand for micro-insurance in Ethiopia. *Journal of Economics and International Finance*, **4(4)**, 79-91.

Tanner, T. and T. Mitchell, 2008: Entrenchment or enhancement: could climate change adaptation help to reduce chronic poverty? *IDS Bulletin*, **39(4)**, 6-15.

Taylor, J.G. and L. Xiaoyun, 2012: China's changing poverty: a middle income country case study. *Journal of International Development*, **24(6)**, 696-713.

Tekken, V. and J.P. Kropp, 2012: Climate-driven or human-induced: indicating severe water scarcity in the Moulouya River Basin (Morocco). *Water*, **4(4)**, 959-982.

Tennant, W.J. and B.C. Hewitson, 2002: Intra-seasonal rainfall characteristics and their importance to the seasonal prediction problem. *International Journal of Climatology*, **22(9)**, 1033-1048.

Teperman, S., 2013: Hurricane Sandy and the greater New York health care system. *The Journal of Trauma and Acute Care Surgery*, **74(6)**, 1401-1410.

Terry, G., 2009: No climate justice without gender justice: an overview of the issues. *Gender & Development*, **17(1)**, 5-18.

Thomas, D.S.G., C. Twyman, H. Osbahr, and B. Hewitson, 2007: Adaptation to climate change and variability: farmer responses to intra-seasonal precipitation trends in South Africa. *Climatic Change*, **83(3)**, 301-322.

Thornton, P.K., P.G. Jones, T. Owiyo, R.L. Kruska, M. Herrero, V. Orindi, S. Bhadwal, P. Kristjanson, A. Notenbaert, and N. Bekele, 2008: Climate change and poverty in Africa: mapping hotspots of vulnerability. *African Journal of Agriculture and Resource Economics*, **2(1)**, 24-44.

Thornton, P., M. Herrero, A. Freeman, O. Mwai, E. Rege, P. Jones, and J. McDermott, 2007: Vulnerability, climate change and livestock – research opportunities and challenges for poverty alleviation. *Journal of Semi-Arid Tropical Agricultural Research*, **4(1)**, 1-23.

Thurlow, J., T. Zhu, and X. Diao, 2009: *The Impact of Climate Variability and Change on Economic Growth and Poverty in Zambia*. IFPRI Discussion Paper 00890, International Food Policy Research Institute (IFPRI), Washington, DC, USA, 72 pp.

Tierney, J.E., M.T. Mayes, N. Meyer, C. Johnson, P.W. Swarzenski, A.S. Cohen, and J.M. Russell, 2010: Late-twentieth-century warming in Lake Tanganyika unprecedented since AD 500. *Nature Geoscience*, **3(6)**, 422-425.

Tompkins, E.L., M.C. Lemos, and E. Boyd, 2008: A less disastrous disaster: managing response to climate-driven hazards in the Cayman Islands and NE Brazil. *Global Environmental Change*, **18(4)**, 736-745.

Trostle, R., D. Marti, S. Rosen, and P. Wescott, 2011: *Why Have Food Commodity Prices Risen Again?* WRS-1103 Economic Research Service/USDA, United States Department of Agriculture (USDA), Washington, DC, USA, 29 pp.

Tschakert, P., 2007: Views from the vulnerable: understanding climatic and other stressors in the Sahel. *Global Environmental Change*, **17(3-4)**, 381-396.

Tschakert, P., R. Tutu, and A. Alcaro, 2011: Embodied experiences of environmental and climatic changes in landscapes of everyday life in Ghana. *Emotion, Space and Society*, May 2013, **7**, 13-25.

Tubiello, F., J. Schmidhuber, M. Howden, P.G. Neofotis, S. Park, E. Fernandes, and D. Thapa, 2008: *Climate Change Response Strategies for Agriculture: Challenges and Opportunities for the 21st Century.* Agriculture and Rural Development Discussion Paper No. 42, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 75 pp.

UN, 2012a: *United Nations Conference on Sustainable Development Outcome Document: The Future We Want.* United Nations, New York, NY, USA, 49 pp., www.uncsd2012.org/content/documents/727The%20Future%20We%20Want%2019%20June%201230pm.pdf.

UN, 2012b: *Realizing the Future We Want for All.* Report to the Secretary General, UN System Task Team, co-chaired by the United Nations Department of Economic and Social Affairs (UN DESA) and the United Nations Development Programme (UNDP), New York, NY, USA, 52 pp.

UN ECLAC, 2005: *Grenada: A Gender Impact Assessment of Hurricane Ivan – Making the Invisible Visible.* LIMITED LC/CAR/L.48, Economic Commission for Latin America and the Caribbean (UN ECLAC), United Nations Development Fund for Women (UNIFEM) and United Nations Development Programme (UNDP), UN ECLAC, Santiago, Chile, 53 pp.

UNCCD, 2011: *Desertification: A Visual Synthesis.* United Nations Convention to Combat Desertification (UNCCD), Bonn, Germany, 50 pp.

UNDP, 1990: *Human Development Report 1990: Concept and Measurement of Human Development.* United Nations Development Program (UNDP), Oxford University Press, Oxford, UK and New York, NY, USA, 189 pp.

UNDP, 1994: *Human Development Report 1994: New Dimensions of Human Security.* United Nations Development Program (UNDP), Oxford University Press, Oxford, UK and New York, NY, USA, 226 pp.

UNDP, 2007: *Human Development Report 2007/8. Fighting Climate Change: Human Solidarity in a Divided World.* United Nations Development Programme (UNDP), Palgrave Macmillan, Houndmills, Basingstoke, Hampshire, UK and New York, NY, USA, 384 pp.

UNDP, 2011a: *Towards an 'Energy Plus' Approach for the Poor: A Review of Good Practices and Lessons Learned.* United Nations Development Programme (UNDP) Asia-Pacific Regional Centre, KEEN Publishing Co. Ltd., Bangkok, Thailand, 107 pp.

UNDP, 2011b: *Human Development Report 2011. Sustainability and Equity: A Better Future for All.* United Nations Development Programme (UNDP), Palgrave Macmillan, Houndmills, Basingstoke, Hampshire, UK and New York, NY, USA, 185 pp.

UNDP, 2011c: *An Analysis of the Impact of the Floods on MDGs in Pakistan.* United Nations Development Programme (UNDP), New York, NY, USA, 125 pp.

UNDP, 2012: *Triple Wins for Sustainable Development*. Case Studies of Sustainable Development in Practice, United Nations Development Programme (UNDP), New York, NY, USA, 67 pp.

UNECA, 2011: *Climate Change and Water Resources of Africa: Challenges, Opportunities and Impacts.* Working Paper No. 5, African Climate Policy Centre (ACPC) of the United Nations Economic Commission for Africa (UNECA), UNECA, Addis Abeba, Ethiopia, 26 pp.

UNFCCC, 2011: *Benefits of the Clean Development Mechanism*. United Nations Framework Convention on Climate Change (UNFCCC), Bonn, Germany, 47 pp.

UNFCCC, 2013: *Clean Development Mechanism.* United Nations Framework Convention on Climate Change (UNFCCC), Bonn, Germany, cdm.unfccc.int/about/ccb/index.html.

UNFPA, 2009: *State of World Population, 2009. Facing a Changing World: Women, Population, and Climate.* United Nations Population Fund (UNFPA), New York, NY, USA, 95 pp.

UNISDR, 2009: *2009 Global Assessment Report on Disaster Risk Reduction: Risk and Poverty in a Changing Climate*. United Nations International Strategy for Disaster Reduction (UNISDR), Geneva, Switzerland, 207 pp.

UNISDR, 2011: *2011 Global Assessment Report on Disaster Risk Reduction: Revealing Risk, Redefining Development.* United Nations International Strategy for Disaster Reduction (UNISDR), Geneva, Switzerland, 178 pp.

UN-REDD, 2011: *The Business Case for Mainstreaming Gender in REDD+.* The United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (UN-REDD), Geneva, Switzerland, 41 pp.

UNRISD, 2010: *Combating Poverty and Inequality: Structural Change, Social Policy and Politics.* United Nations Research Institute for Social Development (UNRISD), UNRISD Publications, Geneva, Switzerland, 360 pp.

Uppal, A., L. Evans, N. Chitkara, P. Patrawalla, M.A. Mooney, D. Addrizzo-Harris, E. Leibert, J. Reibman, L. Rogers, and K.I. Berger, 2013: In search of the silver lining: the impact of Superstorm Sandy on Bellevue Hospital. *Annals of the American Thoracic Society*, **10(2)**, 135-142.

Ürge-Vorsatz, D. and S. Tirado Herrero, 2012: Building synergies between climate change mitigation and energy poverty alleviation. *Energy Policy*, October 2012, **49**, 83-90.

Urwin, K. and A. Jordan, 2008: Does public policy support or undermine climate change adaptation? Exploring policy interplay across different scales of governance. *Global Environmental Change*, **18(1)**, 180-191.

Usman, M.T. and C. Reason, 2004: Dry spell frequencies and their variability over southern Africa. *Climate Research*, **26(3)**, 199-211.

Valdivia, C., A. Seth, J.L. Gilles, M. García, E. Jiménez, J. Cusicanqui, F. Navia, and E. Yucra, 2010: Adapting to climate change in Andean ecosystems: landscapes, capitals, and perceptions shaping rural livelihood strategies and linking knowledge systems. *Annals of the Association of American Geographers*, **100(4)**, 818-834.

Van Dam, C., 2011: Indigenous territories and REDD in Latin America: opportunity or threat? *Forests*, **2(1)**, 394-414.

Van Dijk, T., 2011: Livelihoods, capitals and livelihood trajectories a more sociological conceptualisation. *Progress in Development Studies*, **11(2)**, 101-117.

Van Noordwijk, M., 2010: Climate change, biodiversity, livelihoods and sustainagility in Southeast Asia. In: *Moving Forward: Southeast Asian Perspectives on Climate Change and Biodiversity* [Sajise, P.E., M.V. Ticsay, and J.J.C. Saguiguit (eds.)]. Institute of Southeast Asian Studies (ISEAS) Singapore and the Southeast Asian Regional Center for Graduate Study and Research in Agriculture (SEARCA), Los Baños, Laguna, Philippines, pp. 55-83.

Verburg, P. and R.E. Hecky, 2009: The physics of the warming of Lake Tanganyika by climate change. *Limnology and Oceanography*, **54(6 Pt. 2)**, 2418-2430.

Von Braun, J. and A. Ahmed, 2008: *High Food Prices: The What, Who, and How of Proposed Policy Actions.* Policy Brief, International Food Policy Research Institute (IFPRI), Washington, DC, USA, 12 pp.

Von Braun, J., R.S. Meinzen-Dick, and I.F.P.R. Institute, 2009: *"Land Grabbing" by Foreign Investors in Developing Countries: Risks and Opportunities.* IFPRI Policy Brief No. 13, International Food Policy Research Institute (IFPRI), Washington, DC, USA, 9 pp.

Wassmann, R., S. Jagadish, K. Sumfleth, H. Pathak, G. Howell, A. Ismail, R. Serraj, E. Redona, R. Singh, and S. Heuer, 2009: Chapter 3: Regional vulnerability of climate change impacts on Asian rice production and scope for adaptation. In: *Advances in Agronomy, Vol. 102* [Sparks, D.L. (ed.)]. Elsevier Science and Technology/Academic Press, Waltham, MA, USA, pp. 91-133.

Weinzettel, J., E.G. Hertwich, G.P. Peters, K. Steen-Olsen, and A. Galli, 2013: Affluence drives the global displacement of land use. *Global Environmental Change*, **23(2)**, 433-438.

Wheeler, D., 2011: *Quantifying Vulnerability to Climate Change: Implications for Adaptation Assistance.* CGD Working Paper 240, Center for Global Development (CGD), Washington, DC, USA, 49 pp.

Whittenbury, K., 2013: Climate change, women's health, wellbeing and experiences of gender-based violence in Australia. In: *Research, Action and Policy: Addressing the Gendered Impacts of Climate Change* [Alston, M. and K. Whittenbury (eds.)]. Springer Science, Dordrecht, Netherland, pp. 207-222.

Williams, M., 2010: *Economic Development and the Triple Crisis – Gender Equality Betwixt and Between: The Impact of the Economic, Climate and Food Crises on Women's Empowerment and Wellbeing.* Paper prepared for the Ninth Commonwealth Women's Affairs Ministers Meeting, "Gender Issues in Economic Crisis, Recovery and Beyond: Women as Agents of Transformation", Bridgetown, Barbados, 7-9 June 2010, WAMM(10)(INF)3, Commonwealth Secretariat, London, UK, www.wide-network.ch/pdf/Aktuell_Veranstaltungen/WilliamsPaperGenderEqualityandtheTripleCrisis.pdf.

Willox, A.C., S.L. Harper, J.D. Ford, K. Landman, K. Houle, and V. Edge, 2012: "From this place and of this place:" climate change, sense of place, and health in Nunatsiavut, Canada. *Social Science & Medicine*, **75(3)**, 538-547.

Wittman, H.K. and C. Caron, 2009: Carbon offsets and inequality: social costs and co-benefits in Guatemala and Sri Lanka. *Society and Natural Resources*, **22(8)**, 710-726.

Wolf, J., W.N. Adger, I. Lorenzoni, V. Abrahamson, and R. Raine, 2010: Social capital, individual responses to heat waves and climate change adaptation: an empirical study of two UK cities. *Global Environmental Change*, **20(1)**, 44-52.

World Bank, 2001: *The World Development Report, 2000-01: Attacking Poverty*. The International Bank for Reconstruction and Development / The World Bank, Oxford University Press, New York, NY, USA, 335 pp.

World Bank, 2010: *World Development Report 2010: Development and Climate Change.* The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 417 pp.

World Bank, 2012a: *World Development Report 2012: Gender Equality and Development.* The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 426 pp.

World Bank, 2012b: *Turn Down the Heat: Why a 4°C Warmer World Must be Avoided.* A Report for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 84 pp.

Xu, J., R.E. Grumbine, A. Shrestha, M. Eriksson, X. Yang, Y. Wang, and A. Wilkes, 2009: The melting Himalayas: cascading effects of climate change on water, biodiversity, and livelihoods. *Conservation Biology*, **23(3)**, 520-530.

Yamauchi, F., Y. Yohannes, and A. Quisumbing, 2009: *Natural Disasters, Self-Insurance and Human Capital Investment: Evidence from Bangladesh, Ethiopia and Malawi.* Policy Research Working Paper 4910, the Global Facility for Disaster Reduction and Recovery Unit, Sustainable Development Network, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 26 pp.

Yengoh, G.T., F.A. Armah, E.E. Onumah, and J.O. Odoi, 2010a: Trends in agriculturally-relevant rainfall characteristics for small-scale agriculture in Northern Ghana. *Journal of Agricultural Science*, **2(3)**, 3-14.

Yengoh, G.T., A. Tchuinte, F.A. Armah, and J.O. Odoi, 2010b: Impact of prolonged rainy seasons on food crop production in Cameroon. *Mitigation and Adaptation Strategies for Global Change*, **15(8)**, 825-841.

Yohe, G.W., R.D. Lasco, Q.K. Ahmad, N.W. Arnell, S.J. Cohen, C. Hope, A.C. Janetos, and R.T. Perez, 2007: Perspectives on climate change and sustainability. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 811-841.

Zambian Government, 2011: *Strategic Programme for Climate Resilience.* PPCR/SC.8/8, Meeting of the PPCR Sub-Committee Cape Town, South Africa, June 28 and 29, 2011, Agenda Item 9, Ministry of Finance and National Planning, Republic of Zambia, Luska, Zambia, 82 pp.

Ziervogel, G., S. Bharwani, and T.E. Downing, 2006: Adapting to climate variability: pumpkins, people and policy. *Natural Resources Forum*, **30(4)**, 294-305.

Ziervogel, G., M. Shale, and M. Du, 2010: Climate change adaptation in a developing country context: the case of urban water supply in Cape Town. *Climate and Development*, **2(2)**, 94-110.

Zoomers, A., 2010: Globalisation and the foreignisation of space: seven processes driving the current global land grab. *The Journal of Peasant Studies*, **37(2)**, 429-447.

Zottarelli, L.K., 2008: Post-Hurricane Katrina employment recovery: the interaction of race and place*. *Social Science Quarterly*, **89(3)**, 592-607.

Zotti, M.E., V.T. Tong, L. Kieltyka, and R. Brown-Bryant, 2012: Factors influencing evacuation decisions among high-risk pregnant and postpartum women. In: *The Women of Katrina: How Gender, Race, and Class Matter in an American Disaster* [Emmanuel, D. and E. Enarson (eds.)]. Vanderbilt University Press, Nashville, TN, USA, pp. 90-104.

14 Adaptation Needs and Options

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This chapter should be cited as:
Noble, I.R., S. Huq, Y.A. Anokhin, J. Carmin, D. Goudou, F.P. Lansigan, B. Osman-Elasha, and A. Villamizar, 2014: Adaptation needs and options. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 833-868.

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Executive Summary

Since the Fourth Assessment Report (AR4), the framing of adaptation has moved further from a focus on biophysical vulnerability to the wider social and economic drivers of vulnerability and people's ability to respond (*robust evidence*, *high agreement*). These drivers include the gender, age, health, social status, and ethnicity of individuals and groups, and the institutions in place locally, nationally, regionally, and internationally. Adaptation goals are often expressed in a framework of increasing resilience, which encourages consideration of broad development goals, multiple objectives, and scales of operation, and often better captures the complex interactions between human societies and their environment. The convergence between adaptation and disaster risk management has been further strengthened since AR4, building on the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX). {14.1-3}

Adaptation needs arise when the anticipated risks or experienced impacts of climate change require action to ensure the safety of populations and the security of assets, including ecosystems and their services (*medium evidence*, *medium agreement*). Adaptation needs are the gap between what might happen as the climate changes and what we would desire to happen. The use of the term needs has also shifted with the framing of adaptation. In the National Adaptation Programmes of Action (NAPAs) "needs" were usually discussed in terms of major vulnerabilities and priority adaptation activities, and, in both developing and developed countries, this hazard-based approach with a focus on drivers of impacts and options to moderate them is still used often for urban or regional programs. But more recently, the focus has been on tackling the underlying causes of vulnerability such as informational, capacity, financial, institutional, and technological needs. {14.2}

Engineered and technological adaptation options are still the most common adaptive responses, although there is growing experience of the value for ecosystem-based, institutional, and social measures, including the provision of climate-linked safety nets for those who are most vulnerable (*robust evidence*, *high agreement*). Adaptation measures are increasing and becoming more integrated within wider policy frameworks. Integration, though it remains a challenge, streamlines the adaptation planning and decision-making process and embeds climate-sensitive thinking in existing and new institutions and organizations. This can help avoid mismatches with the objectives of development planning, facilitate the blending of multiple funding streams, and reduce the possibility of maladaptive actions. The increasing complexity of adaptation practice means that institutional learning is an important component of effective adaptation. {14.3}

Approaches to selecting adaptation options continue to emphasize incremental change to reduce impacts while achieving co-benefits, but there is increasing evidence that transformative changes may be necessary in order to prepare for climate impacts (*medium evidence*, *medium agreement*). While no-regret, low-regret, and win-win strategies have attracted the most attention in the past and continue to be applied, there is increasing recognition that an adequate adaptive response will mean acting in the face of continuing uncertainty about the extent of climate change and the nature of its impacts, and that in some cases there are limits to the effectiveness of incremental approaches. While attention to flexibility and safety margins is becoming more common in selecting adaptation options, many see the need for more transformative changes in our perception and paradigms about the nature of climate change, adaptation, and their relationship to other natural and human systems. {14.1, 14.3.4}

Among the many actors and roles associated with successful adaptation, the evidence increasingly suggests two to be critical to progress: those associated with local government and those with the private sector (*medium evidence*, *high agreement*). These two groups will bear increasing responsibility for translating the top-down flow of risk information and financing and in scaling up the bottom-up efforts of communities and households in planning and implementing their selected adaptation actions. Local institutions, including local governments, non-government organizations (NGOs), and civil society organizations, are among the key actors in adaptation but are often limited by lack of resources and capacity and by continuing difficulties in gaining national government or international support, especially in developing countries. {14.2.3} Private entities, from individual farmers and small to medium enterprises (SMEs) to large corporations, will seek to protect and enhance their production systems, supply lines, and markets by pursuing adaptation-related opportunities. These goals will help expand adaptation activities but they may not align with government or community objectives and priorities without coordination and incentives. {14.2.4}

Adaptation assessments, which have evolved in substance and style since AR4, have demonstrably led to a general awareness among decision makers and stakeholders of climate risks and adaptation needs and options. However, such awareness has often not translated into adaptation action (*medium evidence*, *high agreement*). Most of the assessments of adaptation done so far have been restricted to impacts, vulnerability, and adaptation planning, with very few assessing the processes of implementation and evaluation of actual adaptation actions. {14.4.1} Assessments that include both top-down assessments of biophysical climate changes and bottom-up assessments of what makes people and natural systems vulnerable to those changes will help to deliver local solutions to globally derived risks. Also, assessments that are linked more directly to particular decisions and that provide information tailored to facilitate the decision-making process appear to have most consistently led to effective adaptation measures. {14.4.3}

The evidence to support the most valuable metrics of adaptation needs and effectiveness is limited, but increasing (*medium evidence*, *high agreement*). {14.5.2-3} At present, there are conflicting views concerning the choice of metrics, as governments, institutions, communities, and individuals value needs and outcomes differently and many of those values cannot be captured in a comparable way by metrics. {14.5} The demand for metrics to measure adaptation needs and effectiveness is increasing as more resources are directed to adaptation. These indicators that are proving most useful for policy learning are those that track not just process and implementation, but also the extent to which targeted outcomes are occurring. {14.5.2.3}

Maladaptation is a cause of increasing concern to adaptation planners, where intervention in one location or sector could increase the vulnerability of another location or sector, or increase the vulnerability of the target group to future climate change (*medium evidence*, *high agreement*). {14.7.3} The definition of maladaptation used in AR5 has changed subtly to recognize that maladaptation arises not only from inadvertent badly planned adaptation actions, but also from deliberate decisions where wider considerations place greater emphasis on short-term outcomes ahead of longer-term threats, or that discount, or fail to consider, the full range of interactions arising from the planned actions. {14.6.1}

14.1. Introduction

This chapter establishes a foundation for understanding adaptation by reviewing core concepts related to adaptation, with a focus on mapping out broad categories of needs and options. Here we use adaptation needs to refer to circumstances requiring information, resources, and action to ensure safety of populations and security of assets in response to climate impacts. Adaptation options are the array of strategies and measures available and appropriate to address needs. Because identifying needs and selecting and implementing options require the engagement of individuals, organizations, and governments at all levels, this chapter also briefly considers the range of actors involved in these processes and summarizes the risks of maladaptation.

Other chapters in this report, namely Chapter 4 and in particular Section 4.4, and supported by Chapters 3, 5, 6, and 7, deal with the threats of climate change on ecosystems and other predominately natural systems and their prospects and options for adaptation. For the sake of space and clarity this chapter focuses on the socioeconomic systems that support human livelihoods, although it also touches on the services provided by ecosystems (including ecosystem-based adaptation).

This chapter also highlights some important tools for implementing adaptation, namely approaches to assessing needs at national, subnational, and sectoral levels, and the challenges of applying metrics to determine adaptation needs and the effectiveness of adaptation actions. In the course of these discussions, this chapter establishes a foundation for the three adaptation chapters that follow. The existence of adaptation options does not necessarily mean that these options can be implemented when the need arises. Therefore, Chapter 15 examines adaptation planning and implementation, including the challenges faced and how these can be addressed. Chapter 16 focuses on adaptation opportunities and constraints, while Chapter 17 assesses the economics of adaptation to climate change, including the costs and benefits of adaptation and of inaction. This chapter also draws on, and seeks not to repeat, the detailed discussions of human health, well-being, security, livelihoods, and poverty found in Chapters 11, 12, and 13 that are so important to the wider discussion of adaptation. These and other interactions among the adaptation chapters are illustrated in Figure 14-1.

Human and natural systems have a capacity to cope with adverse circumstances but, with continuing climate change, adaptation will be needed to maintain this capacity (IPCC, 2012; see also Section 1.4.1 and Box 2.1). The AR5 definition of adaptation (i.e., "The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate harm or exploit beneficial opportunities. In natural systems, human intervention may facilitate adjustment to expected climate and its effects…") follows the lead of the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) in introducing a degree of purposefulness by adding the phrase "which seeks to moderate" rather than simply "which moderates" as in AR4.[1] Human ability to cope with climate impacts can also be increased by actions that are not anticipatory or purposefully undertaken in response to observed or anticipated climate change, sometimes called unplanned actions. For example, diversifying livelihoods in response to immediate economic factors can increase long-term ability to cope with a changing climate. Such actions were often referred to as autonomous adaptation. However, the use of the term in the literature, including the IPCC reports, has been inconsistent. The term is often used to refer to purposeful adaptation actions carried out by agents without external inputs such as policies, information, or resources (see Chapters 17, 22; Skoufias, 2012), and sometimes to refer to purposeful actions that are reactive to experienced climate impacts, rather than being proactive or anticipatory of them (see Glossary and WGII AR3 Section 18.2.3).

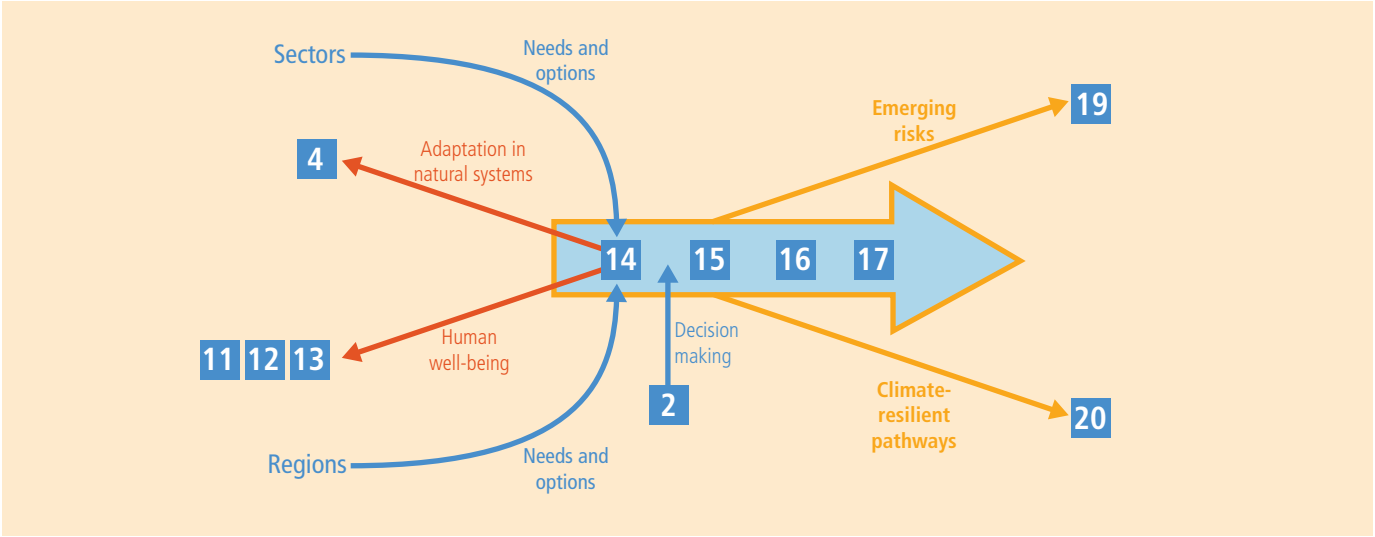

Figure 14-1 | The relationship between the four adaptation chapters (14 to 17) and other closely related chapters. Chapter 14 (Adaptation Needs and Options) draws on and cross-references many of the issues of human well-being, including health, security, and poverty; the treatment of adaptation of natural ecosystems is dealt with mainly in Chapter 4 and is not repeated in Chapter 14. Similarly the needs and options synthesized in Chapter 14 are drawn largely from the sectoral (3 to 10) and regional chapters (21 to 30). Chapter 2 provides input to decision-making approaches relevant to Chapter 15 (Adaptation Planning and Implementation). All the adaptation chapters feed into the synthesis of Chapters 19 (Emerging Risks and Key Vulnerabilities) and 20 (Climate-Resilient Pathways: Adaptation, Mitigation, and Sustainable Development).

The SREX and AR5 definitions of adaptation also clarify the distinction between adaptation in human and natural systems. Natural systems have the potential to adapt through multiple autonomous processes (e.g., phenology changes, migration, compositional changes, phenotypic acclimation, and/or genetic changes), and humans may intervene to promote particular adjustments such as reducing non-climate stresses or through managed migration (see Section 4.5). But successful adaptation will depend on our ability to allow and facilitate natural systems to adjust to a changing climate, thus maintaining the ecosystem services on which all life depends.

Adaptation is becoming increasingly important in climate negotiations and implementation, and integral to AR5 are the terms incremental and transformational adaptation—sometimes referred to as a "paradigm shift" as in the Green Climate Fund Governing Instrument (Green Climate Fund, 2013a). Incremental adaptation refers to actions where the central aim is to maintain the essence and integrity of the existing technological, institutional, governance, and value systems, such as through adjustments to cropping systems via new varieties, changing planting times, or using more efficient irrigation. In contrast, transformational adaptation seeks to change the fundamental attributes of systems in response to actual or expected climate and its effects, often at a scale and ambition greater than incremental activities. It includes changes in activities, such as changing livelihoods from cropping to livestock or by migrating to take up a livelihood elsewhere, and also changes in our perceptions and paradigms about the nature of climate change, adaptation, and their relationship to other natural and human systems (Sections 3.3, 8.6.2.3, 20.5 and FAQ 8.2; IPCC, 2012; Kates et al., 2012; Park et al., 2012; Green Climate Fund, 2013b). Transformational change may be driven by the pursuit of better opportunities or by the realization of the imminent or inevitable limits within existing paradigms (Dow et al., 2013; Section 16.4.2). Transformative change may threaten the status quo for many and require leadership and sometimes triggering events to initiate it (Kates et al., 2012). However, transformational change is not called for in all responses to climate change (Pelling, 2010) and ill-prepared transformative change may bring with it social inequities (O'Brien, 2012). The triggers for transformational change and its implementation are dealt with in more detail in Sections 16.4 and 20.5. Differentiation between incremental and transformative adaptation, although indistinct, is important because it affects how we approach adaptation, how we integrate it into planning and policy, and how we allocate adaptation funding in both developed and developing countries (IPCC, 2012; see also Chapter 17).

Another concept is the adaptation deficit, which is the gap between the current state of a system and a state that would minimize adverse impacts from existing climate conditions and variability (see Glossary); that is, it is essentially inadequate adaptation to the current climate conditions (Burton et al., 2002; Burton, 2004; Burton and May, 2004; Parry et al., 2009; see also Sections 17.2.2.2, 17.6.1). Some have suggested that it is often part of a larger "development deficit" (World Bank, 2010). Delay in action in both mitigation and adaptation will increase the adaptation deficit in many parts of the world (IPCC, 2012).

[1] Purposefulness was introduced in the SREX definition, which introduced the phrase "in order to moderate".

In the process of building future adaptive capacity it is important to reduce the current adaptation deficit along with designing effective risk management and climate change adaptation measures (Hallegatte, 2011). Failure to close the adaptation deficit, both current and in the future, will result in residual damages from climate change. There have been calls for such residual damages to be evaluated and reported (Parry et al., 2009).

Summary of Key Findings from AR4

In the Working Group II (WGII) Fourth Assessment Report (AR4), the main chapter on adaptation (Chapter 18) refined the basic terminology of adaptation and concluded that adaptation to climate change was already taking place, but on a limited basis. Societies have a long record of adapting to the impacts of weather and climate through a range of practices that include crop diversification, irrigation, water management, disaster risk management, and insurance, but climate change, along with other drivers of change, poses novel risks often outside the range of experience.

WGII AR4 found that deliberate adaptation measures in response to anticipated climate change were being implemented by a range of public and private actors, on a limited basis, in both developed and developing countries. These measures are undertaken through policies, investments in infrastructure and technologies, and behavioral change, and they are seldom undertaken in response to climate change alone. Many actions that facilitate adaptation to climate change are undertaken to deal with current extreme events, such as heat waves and cyclones, and are often embedded within broader sectoral initiatives such as water resource planning, coastal defense, and disaster management planning.

WGII AR4 concluded that there are individuals and groups within all societies that have insufficient capacity to adapt to climate change. The capacity to adapt is dynamic and influenced by economic and natural resources, social networks, entitlements, institutions and governance, human resources, and technology. However, high adaptive capacity does not necessarily translate into actions that reduce vulnerability. New planning processes are being implemented to attempt to overcome these barriers at local, regional, and national levels in both developing and developed countries. WGII AR4 noted the establishment of the National Adaptation Programmes of Action (NAPAs) and that some developed countries had established national adaptation policy frameworks. Other conclusions from the WGII AR4 relating to the implementation of adaptation policies and measures, barriers to adaptation, and the economic costs of adaptation are summarized in Chapters 15, 16, and 17 of this report.

14.2. Adaptation Needs

Adaptation involves reducing risk and vulnerability; seeking opportunities; and building the capacity of nations, regions, cities, the private sector, communities, individuals, and natural systems to cope with climate impacts, as well as mobilizing that capacity by implementing decisions and actions (Tompkins et al., 2010). Vulnerability is the "propensity or

predisposition [of a system] to be adversely affected" (see Glossary) and, until AR4, was viewed as comprising three elements: exposure, sensitivity, and adaptive capacity (IPCC, 2007a). However, in IPCC (2012) and in this report, vulnerability focuses only on sensitivity and capacity, with exposure more appropriately incorporated into the concept of risk (see Glossary; IPCC, 2012, Section 2.2).

Adaptation requires adequate information on risks and vulnerabilities in order to identify needs and appropriate adaptation options to reduce risks and build capacity. In framing an approach to adaptation, it is important to engage people with different knowledge, experience, and backgrounds in tackling and reaching a shared approach to addressing the challenges (Preston and Stafford Smith, 2009; Tompkins et al., 2010; Fünfgeld and McEnvoy, 2011; Eakin et al., 2012) Initially, identifying needs was most often based on impact assessments (or risk-hazard approaches), but social vulnerability or resilience assessments are increasingly being used (Fünfgeld and McEnvoy, 2011; Preston et al., 2011b). The risk-hazard framework, drawn primarily from risk and disaster management, focuses on the adverse effects that natural hazards and other climate impacts can have on a given location (Füssel and Klein, 2006). The emphasis in this approach is on the physical and biological aspects of impacts and adaptation (Burton et al., 2002). The social vulnerability framework focuses on the reasons and ways in which individuals, groups, and communities are vulnerable to climate impacts. Here, the focus is on how different factors, such as institutions, shape the socioeconomic conditions that place human populations at risk (Adger and Kelly, 1999; Preston et al., 2011b). There are overlaps and complementarities between these frameworks. Approaches to identifying needs and options are discussed further in the section on assessments (Section 14.4).

Comprehensive assessments typically provide insight into the risks and vulnerabilities that will result from climate change in communities, cities, nations, and ecosystems and, in turn, offer a means to identify the presence of adaptation needs and options for addressing those needs. The term adaptation needs is often used but rarely defined in the adaptation literature. In the wider literature, a need can be seen as a problem that can be solved (McKillip, 1987) or as a gap between current outcomes and desired outcomes (Kaufman and English, 1979). Thus, in this context, adaptation needs are the gap between what might happen as the climate changes and what we would desire to happen. Also, the term adaptation needs is used in several ways in the adaptation literature. A common use is in the sense of the "urgent and immediate needs" relating to the adverse effects of climate change, as in the rationale for the NAPAs, although in this case "needs" were usually discussed in terms of major vulnerabilities and priority adaptation activities (by UNFCCC).[2] The most effective descriptions of these needs combined discussions of climate and non-climate drivers of impacts, and the resources, capacity, information, finance, etc., needed to implement options to moderate those impacts (e.g., GEF, 2002). Assessments of adaptation needs, both in developing and developed countries, have often taken a hazard-based approach with a focus on drivers of impacts and options to moderate them (Moser, 2009; Finzi Hart et al., 2012). But more recently, the focus has been on tackling the underlying causes of vulnerability (Füssel, 2007). One of the few categorizations of needs is that of Burton et al. (2006), who recognized information, capacity, financial, institutional, and technological needs. A similar structure is followed in this chapter. We first discuss biophysical and environmental needs on which all lives ultimately depend. Then we discuss social needs and capacities and how they vary throughout society. Third, we discuss our response to climate risks and impacts and how they are modified by the multitude of institutions through which humans work, ranging from international organizations to community-based efforts. Finally, we touch on resources, including societal needs for information and knowledge and financial resources.

Although needs are specific to particular groups and places, they fit into a set of more general categories as summarized in the sections below. For instance, vulnerability at the national and subnational levels is affected by geographic location, biophysical conditions, institutional and governance arrangements, and resource availability, including access to technology and economic stability (Brooks et al., 2005). At the macro-level, two broad classes of determinants of vulnerability are recognized: biophysical determinants and socioeconomic determinants (Preston et al., 2011a). However, adaptation needs are highly diverse and context specific, for instance, varying between islands even within nations such as the Solomon Islands (Section 29.6.1). Different stakeholder groups and individuals have differential adaptation needs and vulnerabilities. Adaptation needs are also dynamic, and future adaptation needs are highly dependent on the mitigation pathway that is taken. Furthermore, the constraints and limits to adaptation (see Chapter 16) are likely to mean that not all needs will be met, thereby emphasizing the need for monitoring to avoid crossing critical thresholds (Section 19.7.3).

14.2.1. Biophysical and Environmental Needs

Climate change is altering ecological systems, biodiversity, genetic resources, and the benefits derived with ecosystem services (Convention on Biological Diversity, 2009; Mooney et al., 2009; Hoegh-Guldberg, 2011). Climate change is inducing shifts in habitats that often cannot be followed by species (Section 4.3.4.1), leading to changed ecosystems, to local and global extinctions, and to the permanent loss of unique combinations of genes. For instance, González et al. (2010) used observed and modeled changes of global patterns of biome shifts under climate change to conclude that up to half of the terrestrial ecosystems were vulnerable as a result of changes from secondary stressors, such as wildfire and disease, and suggested significant changes to natural resource management plans. In addition to the responses of ecosystems to climatic change, a number of studies have identified impacts on ecosystem services, particularly the effects of climate change on agricultural productivity (Coles and Scott, 2009), freshwater ecosystems (Ormerod et al., 2010), and downstream industries and enterprises (Preston and Stafford Smith, 2009). Ecosystem services that are already under threat from the impacts of climate change include pollination, pest, and disease regulation (Section 4.3.4.4); climate regulation services; and potable water supply (Section 4.3.4.5). Further stressors will limit our options to respond to climate change (Section 14.3.2).

[2] https://unfccc.int/files/cooperation_support/least_developed_countries_portal/napa_project_database/application/pdf/napa_index_by_country.pdf.

Natural systems underpin human livelihoods, health, welfare, food security, and prosperity. Vital ecosystem services that need to be maintained include provisioning services such as food, fiber, and potable water supply; regulating services such as climate regulation, pollination, disease control, and flood control; and supporting services such as primary production and nutrient cycling (Section 4.3.4). Much of the water for human consumption originates on forested lands and the quality of the water is heavily dependent on the conditions of the ecosystems through which it flows. Ocean systems also provide climate regulation services, while coral reefs act as ecological buffers (Section 6.4.1.4). For instance, healthy coastal wetlands and coral reefs can help to protect against storm surges and rising sea levels (Hoegh-Guldberg, 2011), while the maintenance of wetlands and green spaces can control runoff and flooding associated with increases in precipitation (Jentsch and Beierkuhnlein, 2008; Mooney et al., 2009). Meanwhile, fisheries and aquaculture contribute more than 20% to the dietary animal protein of nearly 1.5 billion people (Section 5.4.3.3).

Consequently, there is a need to protect these systems and resources within the changing climate. Goldman et al. (2008) found that research projects focusing on delivering ecosystem services, rather than on biodiversity goals, attracted a wider set of funders and better encompassed the landscapes and the people within them. However, many practices to intervene to improve and maintain ecosystem services are based on limited experience and thus still untested assumptions and limited information (Carpenter et al., 2009). Hence, there is a need to improve understanding and valuation of ecosystem services provided by different adaptation options. There is also an urgent need for appropriate ecosystem monitoring to avoid crossing critical thresholds (see Section 19.7.4).

14.2.2. Social Needs

From a social perspective, vulnerability varies as a consequence of the capacity of groups and individuals to reduce and manage the impacts of climate change. Among the key factors determining vulnerability are gender, age, health, social status, ethnicity, and class (Smit et al., 2001; Adger et al., 2009a). For instance, the vulnerability to health-related impacts of climate change varies as a consequence of geographical location (Section 11.3.1), gender and age (Section 11.3.3), and socioeconomic status (Section 11.3.4). Poverty and persistent inequality may be the most salient of the conditions that shape climate-related vulnerability (Section 13.1.4). Climate change is expected to have a relatively greater impact on the poor as a consequence of their lack of financial resources, poor quality of shelter, reliance on local ecosystem services, exposure to the elements, and limited provision of basic services and their limited resources to recover from an increasing frequency of losses through climate events (Tol et al., 2004; Huq et al., 2007; Kovats and Akhtar, 2008; Patz et al., 2008; Revi, 2008; Allison et al., 2009; Shikanga et al., 2009; Gething et al., 2010; Moser and Satterthwaite, 2010; Rosenzweig et al., 2010; Skoufias et al., 2012). Owing to limited financial resources and often compromised health and nutritional status, the poor, along with the sick and elderly, are at increased risk from trauma, physical and mental illness, and death from climate impacts such as increased pollution, higher indoor temperatures, exposure to toxins and pathogens from floods, and the emergence of new disease vectors (Kasperson and Kasperson, 2001; Haines et al., 2006; Costello et al., 2009, 2011; O'Neill and Ebi, 2009; Tonnang et al., 2010; Ebi, 2011; Harlan and Ruddell, 2011; Huang et al., 2011; McMichael and Lindgren, 2011; Semenza et al., 2012). Climate change, climate variability, and extreme events can erode natural, physical, financial, human, and social and cultural assets (Section 13.2.1.1), and poverty traps arise when climate change, variability, and extreme events make the poor even poorer (Section 13.2.1.4).

Social needs under climate change include understanding emotional and psychological needs. In Australia, it has been found that extreme events such as floods, drought, and bushfire can lead to mental suffering, including post-traumatic stress disorder, resulting in the need for psychological support and counseling (The Climate Institute, 2011). For example, drought can increase suicide rates by 8% (Nicholls et al., 2006). Social psychological adaptation processes powerfully mediate public risk perceptions and understanding, psychological and social impacts, and coping responses, as well as behavioral adaptation (Reser and Swim, 2011). Yet little collaborative work or research has so far focused on the nature and dynamics of individual-level coping and adaptation processes and how they influence responses (Reser et al., 2012).

These individual factors also are often associated with and compounded by community-level conditions. Women often have unequal access to and control over resources, including land titles and water rights (UNDP, 2010; CGIAR, 2012; Verner 2012). Many poor and ethnic minorities live in substandard housing; lack access to basic services, savings, and insurance; have compromised health; and are at threat due to excessive densities, poor access roads, and inadequate access to safe water, sanitation, and drainage (Huq et al., 2007; Kovats and Akhtar, 2008; Revi, 2008; Shikanga et al., 2009; Moser and Satterthwaite, 2010). In rural areas, adaptation needs also are linked to the viability of agricultural activity (Bosello et al., 2009). Climate change will lead to higher prices and increased volatility in agricultural markets, which might undermine global food supply security (Section 9.3.3.3). Geographically, highly vulnerable regions are those exposed to sea level rise and extreme events, overlaid with high concentrations of multidimensional poverty (Section 13.2.2.1). There will be disproportionate impacts on developing countries that are dependent on climate-sensitive activities such as agriculture (Cline, 2007). However, middle-income populations can also be adversely impacted by climate change as a stressor adding to other effects.

The causes and solutions of vulnerability take place at different social, geographic, temporal, and political scales (Ribot, 2010). Therefore, to identify critical needs of populations, and the underlying conditions giving rise to these needs, some social assessments can benefit by looking across institutional domains and by spanning from the local to the national. Local assessments provide a means to identify existing vulnerabilities; the policies, plans, and natural hazards contributing to these vulnerabilities; as well as identifying adaptation actions. Social needs include the range of needs for human security (see Section 12.1.2), which include the universal and culturally specific, material, and non-material elements necessary to people to act on behalf of their interests. More specifically, at this level, social needs can be evaluated in terms of availability of natural, physical, human, political, and financial assets; stability of livelihood; and livelihood strategies (Moser, 2006; Heltberg et al., 2009). Alternatively, regional and national assessments

can provide a basis for ascertaining institutional conditions associated with long-standing inequities and development paths that may need to be addressed in order to generate robust options.

Although different stakeholder groups have specific needs, an overarching adaptation need for communities, households, private sector, and institutions is the need for shared learning on adaptation. Adaptation has itself been referred to as a social learning process (Sections 15.6, 22.4.5.3). In particular, there is the need for human capacity and social capital to implement adaptation actions, including education and access to information (Brooks et al., 2005; Adger, 2006; Smit and Wandel, 2006). Improved information for adaptation can benefit from efforts to combine indigenous and scientific knowledge (Section 12.3).

14.2.3. Institutional Needs

Institutions, informal and formal, are enduring regularities of human action in situations structured by rules, norms, and shared strategies, as well as by the physical world (Crawford and Ostrom, 1995) and as such they provide the enabling environment for implementing adaptation actions (Bryan et al., 2009; Chuku, 2009; Aakre and Rübbelke, 2010; Compston, 2010; Moser and Ekstrom, 2011). These institutions provide the guides, incentives, or constraints that shape the distribution of climate risks, establish incentive structures that can promote adaptation, foster the development of adaptive capacity, and establish protocols for both making and acting on decisions (see Section 14.2.3.2; Chuku, 2009; Agrawal, 2010; Compston, 2010). In many instances, international and national-level policies and programs can facilitate localized strategies through the creation of legal frameworks and the allocation of resources (Adger, 2001; Bulkeley and Betsill, 2005; Corfee-Morlot et al., 2011). Overall, there is a need for effective institutions to identify, develop, and pursue climate-resilient pathways for sustainable development (Sections 20.2, 20.4.2), including strengthening the ability to develop new options through social, institutional, and technological innovation (Section 20.4.3). Chapter 15 further considers the institutional needs to mainstream adaptation into government planning.

Governments at all levels play important roles in advancing adaptation and in enhancing the adaptive capacity and resilience of diverse stakeholder groups. National governments are integral to advancing an adaptation agenda as they decide many of the funding priorities and tradeoffs, develop regulations, promote institutional structures, and provide policy direction to district, state, and local governments. In developing countries, national governments are usually the contact point and initial recipient of international adaptation financing. In some countries, both developed and developing, state governments lead the national government in promoting and implementing adaptation (Mertz et al., 2009). The engagement of national government actors can help mobilize political will, support the creation and maintenance of climate research institutions, establish horizontal networks that promote information sharing (Westerhoff et al., 2011), and, in some cases, facilitate the coordination of budgets and financing mechanisms (Alam et al., 2011; Kalame et al., 2011). Governments have the potential to directly reduce the risk and enhance the adaptive capacity of vulnerable areas and populations by developing and implementing locally appropriate regulations including those related to zoning, storm water management and building codes, and attending to the needs of vulnerable populations through measures such as basic service provision and the promotion of equitable policies and plans (Adger et al., 2003b; Brooks et al., 2005; Nelson et al., 2007; Agrawal and Perrin, 2008; Agrawal, 2010).

Among the important institutions in both developed and developing countries are those associated with local governments[3] as they have a major role in translating goals, policies, actions, and investments between higher levels of international and national government to the many institutions associated with local communities, civil society organizations, and non-government organizations (NGOs). SREX Chapter 5 (IPCC, 2012) extensively assesses the role and importance of the local scale institutions when adapting to extreme weather and climate events, highlighting that extreme weather and climate events are acutely experienced at local levels, and that local knowledge is important for managing impacts (Cutter et al., 2009). As institutional actors, local governments and community institutions influence the distribution of climate risks, mediate between levels of government as well as between social and political processes, and establish incentive structures that affect both individual and collective action at all levels (Agrawal and Perrin, 2008). They are in a pivotal position to promote widespread support for adaptation initiatives, foster intergovernmental coordination, and facilitate implementation, both directly and through mainstreaming into ongoing planning and work activities (Anguelovski and Carmin, 2011; Carmin et al., 2012).

There are a number of ongoing political issues that shape the relationships national and local governments have in managing climate risks (Corfee-Morlot et al., 2011). Governance failure has a significant influence on institutional vulnerability (see Section 19.6.1.3.3). For instance, short-term interests, when dealing with long-term issues, can limit incentives to make investments. Similarly, the proximity that authorities have to interest groups can sway their decisions toward other issues, while the drive to engage the public in planning and other activities can orient priorities in ways that do not support adaptation (Corfee-Morlot et al., 2011). Local governments also may lack institutional capacity or have difficulty gaining coordination among departments as conflicts emerge to obtain scarce resources (Satterthwaite and Dodman, 2009; Hardoy and Romero Lankao, 2011). In Bangladesh, the limited access of local governments to resources has been cited as a barrier to local adaptation (Christensen et al., 2012).

Tompkins et al. (2010) found from a survey of 300 projects identified as adaptive at local government level in the UK that more than half were driven by concerns not directly related to climate change. Nevertheless, there are a number of indicators that demonstrate whether local government has institutionalized and mainstreamed adaptation. These include the presence of an identifiable champion from within government, climate change being an explicit issue in municipal plans, resources

[3] Here local government is used to refer to second or third tiers or lower of government, below national and state or provincial government levels; it includes county, district, council, municipal, and similar levels of government.

dedicated to adaptation, and adaptation incorporated into local political and administrative decision making (Roberts, 2008, 2010).

Overall, it is important to match the appropriate institutional scale with the scale of implementation. For example, the Murray-Darling Basin in Australia includes significant water resources across four states requiring management institutions involving federal, state, and local governments to manage and allocate water use (Hussey and Dovers, 2006; see also Box 25-2). While governments have the potential to influence adaptive capacity, local governments often lack the human and technological capacity or mandate to develop and enforce regulations. Local governments, particularly those in developing countries, are faced with numerous challenges that limit their ability to identify needs and pursue adaptation options. Often, these governments must attend to backlogs of basic and critical services such as housing and water supply or focus their attention on addressing outmoded and outdated infrastructure. They also may lack institutional capacity or have difficulty gaining coordination among departments as conflicts emerge to obtain scarce resources (Hardoy and Romero Lankao, 2011, Villamizar, 2011). Adaptation will require an approach that devolves relevant decision making to the levels where the knowledge and capacity for effective adaptations reside (see Box 25-5). Sowers et al. (2011) maintain that, in the Middle East and North Africa, the largely centralized systems of planning, taxation, and revenue distribution lead to a focus on supply-side issues with little consideration of changing climates and demand management, which renders their populations vulnerable to climate-induced impacts on water resources due to weak integration with local constituencies.

There are critical institutional design issues that can be evaluated in order to understand institutional needs (Agrawal, 2010; Gupta et al., 2010). The first is the extent to which institutions are flexible to handle uncertainty. This includes flexibility across and within institutions to evaluate and reorganize delivery where necessary. The uncertainty associated with climate change, presence of rapidly changing information and conditions, and emerging ideas on how best to foster adaptation requires continual evaluation, learning, and refinement (Agrawal, 2010; Gupta et al., 2010). Second is the extent to which adaptation is or has the potential to be integrated into short- and long-term policy making, planning, and program development (Conway and Schipper, 2011). Third is the potential for effective coordination, communication, and cooperation within and across levels of government and sectors (Schipper, 2009; Agrawal, 2010; Conway and Schipper, 2011). Finally, to promote adaptive capacity, it is important to identify the extent to which institutions are robust enough to attend to the needs of diverse stakeholders and foster their engagement in adaptation decisions and actions (Urwin and Jordan, 2008; Gupta et al., 2010).

14.2.4. Need for Engagement of the Private Sector

The role of the private sector is important in delivering adaptation. Often, the focus falls on the role of the private financial sector in providing risk management options including insurance and finance for large projects (see Sections 15.4.4, 17.5.1). However, the delivery of adaptation actions ranges more widely and spans different types of private enterprise, from small farmers, to small to medium enterprises (SMEs), to multinational companies. KPMG International (2008) used published reports and interviews to identify the sectors where businesses considered they face the greatest climate-related risks. In order of perceived importance, the core risks were regulatory, physical, reputational, and litigation risks. The sectors identified as most at risk included an expected cluster around oil and gas and aviation, and also a group less commonly perceived to be at risk, including health care, the financial sector, tourism, and transport.

Khattri et al. (2010) have described three general ways in which the private sector can become involved in adaptation. The first, internal risk management, is critical to firms and enterprises protecting their own interests and ensuring continuity of supply and markets. The second form of involvement recognizes that business is a stakeholder and therefore needs to participate in public sector and civil society initiatives, such as The New York City Panel on Climate Change, which consists of diverse stakeholders, including representatives from the private sector (Rosenzweig et al., 2011). Third, climate adaptation also provides a wide range of new opportunities to the business community. Even in developing countries, where regulations and markets are often underdeveloped and business risks are high, Khattri et al., (2010) identified opportunities for working in the health care, waste and water management, sanitation, housing, energy, and information sectors through fostering cooperation across government departments and NGOs and promoting public-private partnerships.

Despite broad-scale recognition of the need to adapt, such as the World Economic Forum's (2012) ranking of the failure to adapt as one of the highest global risks and on a par with terrorism, and despite some examples of private sector engagement in adaptation, most assessments conclude that action in each of the potential arenas has been slow to emerge and that sharing of knowledge and experience has been limited (Khattri et al., 2010; Agrawala et al., 2011). KPMG International (2008) concluded that, while companies are well used to managing business risk, they have yet to integrate the long-term risks of climate change into these systems. Nor are they preparing to grasp the competitive advantages that will accrue to those taking early action. Most of the businesses interviewed appeared to be unsure of the scale of the threat and opportunities for their businesses or are awaiting further guidance and action by governments. They have trouble in accessing and applying information on the extent of the threats and impacts from climate change and have yet to engage in the detailed cost-benefit analysis of adaptive actions or inaction. The European Commission (2009), using case studies of both the public and private sectors, in eight countries, came to similar conclusions. A survey by West and Brereton (2013) of Australian businesses also concluded that most were only vaguely aware of the breadth of adaptation actions that may be required and concerned about information sharing and disclosure. The authors suggest a framework for disclosures of relevant business activities to both improve practice and cater for the needs of company boards, investors, and stakeholders. A survey commissioned by the Carbon Disclosure Project (Gardiner et al., 2007) found that among Standard and Poor's (S&P) 500 companies many more (about two-thirds of respondents) were prepared to report and share information on managing climate risks and adaptation plans than they were on mitigation.

Also, there are still questions of whether and how adaptation finance should be made available to the private sector in developing countries

and under what circumstances (Persson et al., 2009; IFC, 2010; Agrawala et al., 2011), although this is being piloted through the Pilot Program for Climate Resilience (World Bank, 2008; IFC, 2010). Private sector engagement and investment in adaptation is expected to make a substantial contribution to reducing climate risk, but the distribution of its investments will be selective and will be unlikely to match government and civil priorities (Atteridge, 2011).

14.2.5. Information, Capacity, and Resource Needs

Successful implementation of adaptation actions depends on the availability of information, access to technology and funding (Yohe and Tol, 2001; Adger, 2006; Eakin and Lemos, 2006; Smit and Wandel, 2006; World Bank, 2010). In some cases a supposed lack of relevant and legitimate information has been used as a rationale for inaction (Moser and Ekstrom, 2011). To address this concern, the Nairobi Work Program—established at COP-12 in 2006, with a goal of helping developing countries make better informed decisions based on sound scientific, technical, and socioeconomic data—has included repeated calls for better observation systems, information sharing, and modeling capacity (UNFCCC/SBSTA/2008/3). Developed and developing countries have acted on this priority by establishing institutions to provide information services at national, regional, and global scales (CCCCC, 2011; UKCIP, 2011; NCCARF, 2012), and there is an ongoing need to promote information acquisition and dissemination (OECD, 2009). For example, information-related adaptation needs in Africa include additional vulnerability and impact assessments with greater continuity, country-specific socioeconomic scenarios, and greater knowledge on costs and benefits of different adaptation measures (Section 22.4.2). Research and development, knowledge, and technology transfer are also important for promoting adaptive capacity. However, providing information does not mean that users will be able to make effective use of it, and this information will often have to be tailored or translated to the individual context (Webb and Beh, 2013). Efficacy of scientific knowledge can be improved by calibration with indigenous knowledge (Section 20.4.2). There are also opportunities for technology transfer and innovation to be enhanced through information technologies (Section 20.4.3).

Financial resources for adaptation have been slower to become available for adaptation than for mitigation in both developed and developing countries (see Chapter 17). Adaptation finance made up probably only a fifth of initial allocations of fast-start funding (Ciplet et al., 2012); and much of this funding has been directed toward capacity-building, standalone projects, or pilot programs. This not only has left financial needs, but has also meant that there is less expertise in adaptation assessment and implementation, which is further confounded by the complex relationship between adaptation and more common sustainable development and/or poverty reduction planning (McGray et al., 2007). Adaptation cost estimates have been used to estimate the financial needs for adaptation, and these may well have been underestimated (see Section 17.4).

Overall, at both international and national levels there is a need to develop financial instruments that are equitable in both their delivery of resources and in sharing the burden of supporting the instruments (Levina, 2007; World Bank, 2010; see also Chapters 16, 17). In this regard, the Green Climate Fund (GCF) was established in 2010, based on the commitment by developed country parties to mobilize jointly US$100 billion per year by 2020 to address the needs of developing countries (UNFCCC, 2007). Deliberation over how adaptation finance needs will be met has become central to the UNFCCC policy agenda (Section 16.3.4). Also, financial mechanisms for disaster risk management are also inextricably linked with those for adaptation (Mechler et al., 2010). Lessons from recent recovery operations have emphasized the need for disaster preparedness along with longer term goals directed to building resilience, including maximizing the employment-creation benefits of adaptation measures (Harsdorff et al., 2011.)

Finances required in the future for climate change are estimated to approach levels on the order of current development expenditure, and there is a large gap in funding available for climate change responses in developing countries (Peskett et al., 2009). Therefore, there is a related need to design delivery channels so that funding benefits the poor, as they often are most vulnerable to the impacts of climate change and climate-related disasters. As well as channeling adaptation finance to governments, there is a need for finance to reach the most vulnerable people and for approaches to enable stakeholder participation (Section 15.2.3). For example, for adaptation financing, working at the subnational level will be important and mechanisms such as microfinance may be effective (Agrawala and Carraro, 2010). Another important concern is that, with new money being made available for climate change research, policy development, and practice, people may place too much emphasis on addressing climate change as an isolated priority to the detriment of other equally pressing social, economic, and environmental issues (Ziervogel and Taylor, 2008). For example, in small islands, there are concerns that placing adaptation above the critical development needs of the present could inadvertently reduce resilience (see Section 29.6).

14.3. Adaptation Options

Identifying needs stemming from climate risks and vulnerabilities provides a foundation for selecting adaptation options. Over the years, a number of categories of options have been identified. These options include a wide range of actions that, as summarized in Table 14-1, are organized into three general categories: structural/physical, social, and institutional.

There are many different ways that the range of adaptation options available could be categorized (Burton, 1996), thus any categorization is unlikely to be universally agreed on; but this aims to take into account the diversity of adaptation options for different sectors and stakeholders. Some options cut across several categories. National, sectoral, or local adaptation plans are likely to include a number of measures that are implemented jointly from across various categories including structural, institutional, and social options. Furthermore, some adaptation options are interrelated. For instance, institutions and information are prerequisites for effective early warning systems.

Adaptation constraints and limits mean not all adaptation needs will be met, and not all adaptation options will be possible (see Chapter 16,

Table 14-1 | Categories and examples of adaptation options.

Category		Examples of options*
Structural/ physical	Engineered and built environment	Sea walls and coastal protection structures (5.5.2 and 24.4.3.5; Figure 5-5); flood levees and culverts (26.3.3); water storage and pump storage (Section 23.3.4); sewage works (3.5.2.3); improved drainage (24.4.5.5); beach nourishment (5.4.2.1); flood and cyclone shelters (11.7); building codes (Section 8.1.5); storm and waste water management (8.2.4.1); transport and road infrastructure adaptation (8.3.3.6); floating houses (8.3.3.4); adjusting power plants and electricity grids (10.2.2; Table 10-2)
	Technological	New crop and animal varieties (7.5.1.1.1, 7.5.1.1.3, 7.5.1.3; Box 9-3; Table 9-7); genetic techniques (27.3.4.2); traditional technologies and methods (7.5.2, 27.3.4.2, 28.2.6.1, and 29.6.2.1); efficient irrigation (10.3.6 and 22.4.5.7; Box 20-4); water saving technologies (24.4.1.5 and 26.3.3) including rainwater harvesting (8.3.3.4); conservation agriculture (9.4.3.1 and 22.4.5.7); food storage and preservation facilities (22.4.5.7); hazard mapping and monitoring technology (15.3.2.3 and 28.4.1); early warning systems (7.5.1.1, 8.1.4.2, 8.3.3.3, 11.7.3, 15.4.3.2, 18.6.4, 22.2.2.1, 22.3.5.3, and 22.4.5.2); building insulation (8.3.3.3); mechanical and passive cooling (8.3.3.3); renewable energy technologies (29.7.2); second-generation biofuels (27.3.6.2)
	Ecosystem-based[a]	Cross Chapter Box CC-EA, Ecological restoration (5.5.2, 5.5.7, 9.4.3.3, and 27.3.2.2; Box 15-1) including wetland and floodplain conservation and restoration; increasing biological diversity (26.4.3); afforestation and reforestation (Box 22-2); conservation and replanting mangrove forest (15.3.4 and 29.7.2); bushfire reduction and prescribed fire (Section 24.4.2.5; Box 26-2); green infrastructure (e.g., shade trees, green roofs) (8.2.4.5, 8.3.3, 11.7.4, and 23.7.4); controlling overfishing (28.2.5.1 and 30.6.1); fisheries co-management (9.4.3.4 and 27.3.3.1); assisted migration or managed translocation (4.4.2.4, 24.4.2.5, 24.4.3.5, and 25.6.2.3); ecological corridors (4.4.2.4); ex situ conservation and seed banks (4.4.2.5); community-based natural resource management (CBNRM) (22.4.5.6); adaptive land use management (Section 23.6.2)
	Services	Social safety nets and social protection (Box 13-2; 8.3, 17.5.1, and 22.4.5.2); food banks and distribution of food surplus (29.6.2.1); municipal services including water and sanitation (3.5.2.3 and 8.3.3.4); vaccination programs (11.7.1), essential public health services (11.7.2) including reproductive health services (11.9.2) and enhanced emergency medical services (8.3.3.8); international trade (9.3, 9.4, and 23.9.2)
Social	Educational	Awareness raising and integrating into education (11.7, 15.2, and 22.4.5.5); gender equity in education (Box 9-2); extension services (9.4.4); sharing local and traditional knowledge (12.3.4 and 28.4.1) including integrating into adaptation planning (29.6.2.1); participatory action research and social learning (22.4.5.3); community surveys (Section 8.4.2.2); knowledge-sharing and learning platforms (8.3.2.2, 8.4.2.4, 15.2.4.2, and 22.4.5.4); international conferences and research networks (8.4.2.5); communication through media (22.4.5.5)
	Informational	Hazard and vulnerability mapping (11.7.2, 8.4.1.5); early warning and response systems (15.4.2.3 and 22.4.5.2) including health early warning systems (11.7.3, 23.5.1, 24.4.6.5, and 26.6.3); systematic monitoring and remote sensing (15.4.2.1 and 28.6); climate services (2.3.3) including improved forecasts (27.3.4.2); downscaling climate scenarios (8.4.1.5); longitudinal data sets (26.6.2); integrating indigenous climate observations (22.4.5.4, 25.8.2.1, and 28.2.6.1); community-based adaptation plans (5.5.1.4 and 24.4.6.5) including community-driven slum upgrading (8.3.2.2) and participatory scenario development (22.4.4.5)
	Behavioral	Accommodation (5.5.2); household preparation and evacuation planning (23.7.3); retreat (5.5.2) and migration (29.6.2.4), which has its own implications for human health (11.7.4) and human security (12.4.2); soil and water conservation (23.6.2 and 27.3.4.2); livelihood diversification (7.5.1.1, 7.5.2, and 22.4.5.2); changing livestock and aquaculture practices (7.5.1.1); crop-switching (22.3.4.1); changing cropping practices, patterns, and planting dates (7.5.1.1.1, 23.4.1, 26.5.4, and 27.3.4.2; Table 24-2); silvicultural options (25.7.1.2); reliance on social networks (Section 29.6.2.2)
Institutional	Economic	Financial incentives including taxes and subsidies (Box 8-4; 8.4.3 and 17.5.6); insurance (8.4.2.3, 13.3.2.2, 15.2.4.6, 17.5.1, 26.7.4.3, and 29.6.2.2; Box 25-7) including index-based weather insurance schemes (9.4.2 and 22.4.5.2); catastrophe bonds (8.4.2.3 and 10.7.5.1); revolving funds (8.4.3.1); payments for ecosystem services (9.4.3.3 and 27.6.2; Table 27-7); water tariffs (8.3.3.4.1 and 17.5.3); savings groups (8.4.2.3 and 11.7.4; Box 9-4); microfinance (Box 8-3; 22.4.5.2); disaster contingency funds (22.4.5.2 and 26.7.4.3); cash transfers (Box 13-2)
	Laws and regulations	Land zoning laws (22.4.4.2 and 23.7.4); building standards (8.3.2.2, 10.7.5, and 22.4.5.7); easements (27.3.3.2); water regulations and agreements (26.3.4 and 27.3.1.2); laws to support disaster risk reduction (8.3.2.2); laws to encourage insurance purchasing (10.7.6.2); defining property rights and land tenure security (22.4.6 and 24.4.6.5); protected areas (4.4.2.2); marine protected areas (Box CC-CR Chapter 6; 23.6.5 and 27.3.3.2); fishing quotas (23.9.2); patent pools and technology transfer (15.4.3 and 17.5.5)
	Government policies and programs	National and regional adaptation plans (15.2 and 22.4.4.2; Box 23-3) including mainstreaming climate change; sub-national and local adaptation plans (15.2.1.3 and 22.4.4.4; Box 23-3); urban upgrading programs (8.3.2.2); municipal water management programs (8.3.3.4; Box 25-2); disaster planning and preparedness (11.7); city-level plans (8.3.3.3 and 27.3.5.2; Boxes 26-3 and 27-1), district-level plans (26.3.3), sector plans (26.5.4), which may include integrated water resource management (3.6.1 and 23.7.2), landscape and watershed management (4.4.2.3), integrated coastal zone management (2.4.3, 5.5.4.1, and 23.7.1), adaptive management (2.2.1.3 and 5.5.1.4; Box 5-2), ecosystem-based management (6.4.2.1), sustainable forest management (2.3.4), fisheries management (7.5.1.1.3 and 30.6.2.1), and community-based adaptation (5.5.4.1, 8.4, 15.2.2, 21.3.2, 22.4.4.5, 24.5.2, 29.6.2.2, and 29.6.2.3; Tables 5-4 and 8-4; FAQ 15.1)

Notes: These adaptation options should be considered overlapping rather than discrete, and are often pursued simultaneously as part of adaptation plans. Examples given can be relevant to more than one category.

[a]A number of these would fall under the term "green infrastructure" in some European Commission documents (European Commission, 2009).
*WGII AR5 sections containing representative sample of adaptation options.

particularly Section 16.7.1). Moreover, adaptation options are not available to meet all adaptation needs. For instance, adaptation options are poorly developed for the broader set of impacts on ocean systems (see Section 30.6). There is also often going to be a gap between adaptation needs and the effectiveness of the options to meet these needs even when well resourced and well implemented. Some of this gap may be met by procedures to deal with loss and damage (Section 19.7) and some adaptation deficit will remain with us. Many of the adaptation options intersect with vulnerability reduction and development options that build adaptive capacity and address the "adaptation deficit" which may be seen as part of a wider "development deficit" (McGray et al., 2007; see also Section 2.4.2).

14.3.1. Structural and Physical Options

This category highlights adaptation options that are discrete, with clear outputs and outcomes that are well defined in scope, space, and time. They include structural and engineering options; the application of discrete technologies; the use of ecosystems and their services to serve adaptation needs; and the delivery of specific services at the national, regional, and local levels. This category includes much of the notion of "concrete activities" that reflect the priority of the Adaptation Fund, where the focus is on "discrete activities with a collective objective(s) and concrete outcomes and outputs that are more narrowly defined in scope, space, and time" (Adaptation Fund Board, 2013).

14.3.1.1. Engineering and Built Environment

Engineering, and the multidisciplinary teams engineers work with (architects, planners, legal experts, etc.), is often at the forefront of delivering adaptation technologies and strategies (Dawson, 2007). Most engineering options are expert driven, capital-intensive, large-scale, and highly complex (McEvoy et al., 2006; Morecroft and Cowan, 2010; Sovacool, 2011). While many of the engineering options—including management of storm and waste water flow (both inland and coastal), flood levees, seawalls, upgrading existing infrastructures to improve wind and flooding resilience, beach nourishment, and retrofitting buildings (Blanco et al., 2009; Koetse and Rietveld, 2012; Ranger and Garbett-Shiels, 2012)—are extensions and improvements of existing practices, plans, and structures; some newer projects are now integrating changed climate risk into the initial design. For example, during the engineering design of the Qinghai-Tibet Railway, various measures were proposed to ensure the stability of the railway embankment in permafrost regions (Wu et al., 2008). Section 5.5.4.1 describes how new coastal protection structures in Japan are being upgraded to take into account future sea level rise.

Engineered adaptation options typically have two general limitations. First, they often must cope with uncertainties associated with projecting climate impacts arising from assumptions about future weather, population growth, and human behavior (Dawson, 2007; Furlow et al., 2011). Second, the longevity and cost of engineered infrastructure affect the feasibility at the outset (Koetse and Rietveld, 2012). They also are subject to consequences that were not anticipated. For example, after coastal eastern England was devastated by the North Sea storm surge in 1953, hard-engineered sea walls were put in place to protect the coast from erosion and inundation. However, the engineered alterations resulted in a new array of coastal instabilities, including disturbances in sediment supply and damages to coastal ecosystems (Adger et al., 2009b; Turner et al., 2010). As a result, many have promoted a "phased capacity expansion" strategy, which allows engineered projects to undertake design modification as conditions or knowledge change and facilitate incremental project construction to ease the burden of upfront financing (Colombo and Byer, 2012). An example is the Thames Estuary 2100 Plan (see Box 5-1) and, in the Netherlands, the Delta Works (Arnold et al., 2011).

14.3.1.2. Technological Options

Recent advances in technology and information are being combined with engineering structural adaptation measures in various applications. In the food and agriculture sector, a suite of adaptation options have been developed and applied to reduce the adverse impacts of climate change on production (FAO, 2007; Stokes and Howden, 2010; see also Chapters 7, 9). Technologies range from more efficient irrigation and fertilization methods, plant breeding for greater drought tolerance, and adjusting planting based on projected yields (Semenov, 2006, 2008; Bannayan and Hoogenboom, 2008) to transfers of traditional technologies such as floating gardens (Irfanullah et al., 2011a,b). Technology options for climate change adaptation include both "hard" and "soft" technologies, and not only new technologies but also indigenous and locally made appropriate technology (Glatzel et al., 2012). For example, traditional construction methods have been identified across the Pacific as a means of adapting to tropical cyclones and floods, including building low aerodynamic houses and the use of traditional roofing material such as sago palm leaves to reduce the hazard of iron roofing being blown away in high winds (see Section 29.6.2.1). Centralized high-technology systems can increase efficiency under normal conditions, but also risk cascading malfunctions in emergencies (Section 15.4.3).

With the rapid diffusion of Information and Communication Technologies (ICT) such as mobile phones and the Internet, the unprecedented speed at which information is produced and shared is posing a new set of possibilities for communication. ICT provides opportunities for top-down dissemination of relevant information such as weather forecasts, hazard warnings, market information, information sharing, and advisory services. It can also generate essential information through bottom-up processes such as "crowd sourcing" of useful information such as local flood levels, disease outbreaks, and the management of disaster responses. MacLean (2008) identifies three kinds of effects of the rapid advances in ICT on adaptation and development in general: direct use for monitoring and measuring climate change as described earlier, as a medium for raising awareness, and as an enabler for a "networked governance" based on networked open organizations. Pant and Heeks (2011) emphasize the difficulty in foreseeing additional applications arising from planned ICT applications exploiting local creativity and entrepreneurship, but warn that ICT itself is not a panacea and that the most effective applications are embedded in other societal behaviors.

There are repeated calls for technology transfer to and sharing between developing countries in adaptation to match the programs associated with mitigation (UNFCCC, 2006). Unlike mitigation, where low-carbon technologies are often new and protected by patents held in developed countries, in adaptation the technologies are often familiar and applied elsewhere. For example, agricultural practices that are well known in a region some distance away may now be applicable but unfamiliar within a region of interest (Irfanullah et al., 2011a). Thus, technology transfer in adaptation may be easier than for mitigation. For example, to address water scarcity issues in many places, water storage, use, and water efficiency technologies will all need to be more widely available. See also Section 15.3.4 on technology transfer and diffusion.

14.3.1.3. Ecosystem-Based Adaptation

Ecosystem-based adaptation (EBA)—which is the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change (Convention on Biological Diversity, 2009)—is becoming an integral approach to adaptation (see Box CC-EA). Often, when faced with climate-related threats, first consideration is given to engineered and technological approaches to adaptation. However, working with nature's capacity and pursing ecological options, such as coastal and wetland maintenance and restoration, to absorb or control the impact of climate change in urban and rural areas can be efficient and effective means of adapting (Huntjens et al., 2010; Jones et al., 2012). The use of mangroves and salt marshes as a buffer against damage to coastal communities and infrastructure has been well researched and found to be effective both physically and financially in appropriate locations (Day et al., 2007;

Morris, 2007). They can also provide biodiversity co-benefits, support fish nurseries, and have carbon sequestration value (Adger et al., 2005; Reid and Huq, 2005; Convention on Biological Diversity, 2009). Other EBA activities include integrative adaptive forest management (Bolte et al., 2009; Guariguata, 2009; Reyer et al., 2009), and the use of agro-ecosystems in farming systems (Tengö and Belfrage, 2004), ecotourism activities (Adler et al., 2013), land and water protection and management, and direct species management (Mawdsley et al., 2009). An analysis of the 44 submitted NAPAs showed that the value of ecosystem services was acknowledged in 50% of the national proposals and, in 22% of the proposals, included the use of ecosystem services mostly in support of other adaptation activities including infrastructure, soil conservation, and water regulation (Pramova et al., 2012).

Green infrastructure (including the use of green roofs, porous pavements, and urban parks) can improve storm water management and reduce flood risk in cities, and can moderate the heat-island effect, as well as having co-benefits for mitigation (Section 8.3.3.7). For example, New York City has a well-established program to enhance its water supply through watershed protection that is cost-effective compared to constructing a filtration plant (Section 8.3.3.7). However, there are trade-offs relating to land use and the availability of space for people and social, economic, and environmental activities. For example, providing an effective wetland buffer for coastal protection may require emphasis on silt accumulation possibly at the expense of wildlife values and recreation (Convention on Biological Diversity, 2009; Dudley et al., 2010). Similarly Goldstein et al. (2012) found that in land use decision making in Hawaii trade-offs existed between carbon storage and water quality, and between environmental improvement and financial returns. A further consideration is that ecosystem-based approaches are often more difficult to implement and assess as they usually require cooperation across institutions, sectors, and communities, and their benefits are also spread across a similarly wide set of stakeholders (Jones et al., 2012). One of the major barriers to EBA is the lack of comparable standards and methodologies applied to engineering approaches, thus demonstrating the need for more dialog between engineering and ecological communities.

14.3.1.4. Service Options

Service provision consists of a diverse range of specific and measurable activities. For instance, one measure to support the most vulnerable populations is social safety nets. Efforts to address child malnutrition, which often result from loss of livelihood due to extreme weather events, particularly floods and droughts (Hoddinott et al., 2008; Alderman et al., 2009), offer an example of how safety nets can serve as a climate adaptation measure. While some studies have shown that food programs can be counterproductive to promoting livelihoods over the longer term or may not prevent malnutrition in non-emergency situations (e.g., Bhutta et al., 2008), programs designed to provide support via food programs, micro-finance, or insurance at times of extreme events can provide an important bridge for vulnerable populations (Hoeppe and Gurenko, 2006; Hochrainer et al., 2007; Alderman et al., 2009; Meze-Hausken et al., 2009).

Public health services also are important for tackling projected increases of disease incidences spurred on by climate change (Ebi and Burton, 2008; Garg et al., 2009; Edwards et al., 2011; Huang et al., 2011). For example, in countries where malaria is endemic, frequent adaptation options for addressing possible outbreaks include increasing use of mosquito nets, insecticides sprays, and controlling mosquito breeding by reclaiming land and filling drains (Garg et al., 2009). Governments at all levels are often also responsible for maintaining adequate access to services that are projected to be further stressed due to climate change (Laukkonen et al., 2009). Frequently cited options in this domain include, among others, clearing drainage systems to prevent floods, diversifying water supply services to account for changing water supplies (Kiparsky et al., 2012), and maintaining open public spaces dedicated for disaster recovery and other emergency purposes (Hamin and Gurran, 2009).

At the local level, infrastructure associated with the provision of basic services, such as water, sanitation, solid waste disposal, power, storm water and roadway management, and public transportation are integral to increasing adaptive capacity (Paavola, 2008; Bambrick et al., 2011; Barron et al., 2012; see also Section 8.2.4.1). Transport links enable households to take part in trade, for example, to access agricultural markets (Section 9.3.3.3.2) although supply chains can be vulnerable to climate disruption. Housing services are particularly critical because new patterns in temperature and precipitation will alter the habitability and stability of residences while increased frequency and intensity of natural disasters will place settlements and homes on both stable and unstable land at greater risk (Satterthwaite and Dodman, 2009; see also Section 8.3.3.3). Although one option is to relocate people inhabiting vulnerable areas, some argue that *in situ* upgrading may be more cost-effective, especially for addressing informal settlements in developing countries (Revi, 2008).

14.3.2. Social Options

There are various adaptation options that target the specific vulnerability of disadvantaged groups, including targeting vulnerability reduction and social inequities. Community-based adaptation (CBA) refers to the generation and implementation of locally driven adaptation strategies, operating on a learning-by-doing, bottom-up, empowerment paradigm that cuts across sectors and technological, social, and institutional processes. Social protection schemes (see also Section 14.3.1 on services) include public and private initiatives that transfer income or assets to the poor, protect against livelihood risks, and raise the social status and rights of those who are marginalized (see Box 13-2). An example of a social protection scheme aimed at moving beyond repeated relief interventions is Ethiopia's Productive Safety Net Program (PSNP) (Section 22.4.5.2).

The complexity of climate adaptation means that adaptation options are heavily influenced by forms of learning and knowledge sharing (Collins and Ison, 2009). Many scholars have noted that education is a key indicator for how people select adaptation options (Chinowsky et al., 2011; Sovacool et al., 2012), while a lack of education is a constraint that contributes to vulnerability (Paavola, 2008). For example, in a study of how farmers in the Nile Basin of Ethiopia select adaptation options, the researchers found a positive relationship between the education level of the household head and the adoption of improved technologies and adaptation to climate change (Deressa et al., 2009a,b). In Bangladesh,

education about disaster responses was greatly assisted by rising literacy rates, especially among women (Section 11.7).

Awareness raising, extension, outreach, community meetings, and other educational programs are important for disseminating knowledge about adaptation options (Aakre and Rübbelke, 2010; Birkmann and Teichman, 2010) as well as for helping to build social capital that is critical for social resilience (Adger, 2003; Krasny et al., 2010; Wolf et al., 2010). In this regard, education can be seen as a public good that promotes dialog and networks (Boyd and Osbahr, 2010), and therefore allows the development of resilience at both the level of the individual learner and at the level of socio-ecological systems (Krasny et al., 2010). Research partnerships and networks can facilitate knowledge-sharing and awareness raising at all levels from small groups of individuals to large institutions (Section 8.4.2.5). Communication and dialog on adaptation can be a two-way flow of information. Adaptation has itself been described as a social learning process (Section 15.3.1.2), and a number of initiatives in Africa emphasized the importance of iterative and experiential learning for flexible adaptation planning (Suarez et al., 2009; see also Section 22.4.5.3). In Maryland a half-day role-playing process has been designed to both help local people, working with key local and state experts and planners, to plan and prepare for sea level rise and other coastal impacts. It allows them to experience first hand the diversity of stakeholders, the conflicting decisions to be made, and the need to communicate throughout their community to adapt to new risks (Anon, 2009). A similar role-playing game has been developed for the Chesapeake Bay of the eastern United States (Learmonth et al., 2011).

Informational strategies are integral to adaptation. Early warning systems are critical to ensuring awareness of natural hazards and to promoting timely response, including evacuation. A number of approaches are being employed around the world, including tone alert radio, emergency alert system, presentations, and briefings (Van Aalst et al., 2008; Ferrara de Giner et al., 2012). Heat wave and health warning systems (HHWS) can be designed to prevent negative health impacts, by predicting possible health outcomes, identifying triggers, and communicating prevention responses (Section 11.7.3).

Climate services initially emerged as an expansion of the tasks provided by weather services, and can act as "knowledge brokers" that establish a dialog between science and the public, to facilitate decision support (Section 2.4.1.2). Linking indigenous and conventional climate observations can add value, for example, in western Kenya, where scientists have worked with local rainmakers to develop consensus forecasts (Section 22.4.5.4). Awareness raising through scenario development, computer modeling, and role playing is effective in preparing both responsible authorities and the public. As previously noted, ICT is facilitating rapid dissemination of information. However, low-tech measures such as brochures, public service announcements, and direct contact with local residents also are important to fostering awareness and response especially where access to ICT is limited or expensive (National Research Council, 2011).

Behavioral measures are among the suite of options that are integral to advancing climate adaptation. Government incentives can spark behavioral change. For example, to slow runoff into storm sewers and reduce flooding, a number of cities in the USA run "Disconnect your Downspout" programs to urge homeowners to redirect water from their roof into a storage tank or small wetlands. These programs will provide information to households and some offer rebates on supplies. Many poor and vulnerable communities have taken steps to adapt to changes in climate, particularly those in flood-prone areas. For instance, some local communities in Manila are increasing the number of floors in homes and building makeshift bridges (Porio, 2011). Behavioral adaptation can include livelihood diversification, which has long been used by African households to cope with climate shocks and spread risk (Section 22.4.5.2). Labor migration can be an important strategy for reducing vulnerability to different sources of stress as it helps households diversify their livelihoods (Banerjee et al., 2013). However, migration and relocation do have implications for family relations, health, and human security (see Sections 11.7.4, 12.4.2).

14.3.3. Institutional Options

Numerous institutional measures can be used to foster adaptation. These range from economic instruments such as taxes, subsidies, and insurance arrangements to social policies and regulations (de Bruin et al., 2009; Hallegatte, 2009; Heltberg et al., 2009). For instance, in the USA, post-disaster funds for loss reduction are added to funds provided for disaster recovery and can be used to buy out properties that have experienced repetitive flood losses and to relocate residents to safer locations, to elevate structures, and to assist communities with purchasing property and altering land-use patterns in flood-prone areas, as well as undertaking other activities designed to lessen the impacts of future disasters not only on habitation but also on more effective food production and other livelihoods (FEMA, 2010). Uptake of climate risk insurance is hindered by expensive premiums. The Caribbean Catastrophe Risk Insurance Facility (CCRIF) pools together country-level risks into a more diversified portfolio to offer lower premiums for immediate post-disaster responses (Section 29.6.2.2).

Laws, regulations, and planning measures such as protected areas, building codes, and re-zoning are institutional measures that can improve the safety of hazard-prone communities by designating land use to support resilience (Biderman et al., 2008; Bartlett et al., 2009). For example, marine protected areas (MPAs) have the potential to increase ecosystem resilience and increase recovery of coral reefs after mass coral bleaching (see Chapter 6, Box CC-CR). While zoning can be used to procure sites for low-income populations (Biderman et al., 2008; Bartlett et al., 2009; Satterthwaite and Dodman, 2009), if it increases property and housing values it also has the potential to exclude the poor from these areas. Legal rights can also determine adaptive capacity as well as access to resources. Land tenure security in Africa is widely accepted as being critical for enabling people to make longer-term decisions, such as changing farming practices (Section 22.4.6).

A number of funding and financial issues are linked to institutions. At the international level, agreements and donors have a critical role to play in promoting and supporting the allocation and flow of financial resources (OECD, 2011). For instance, the Adaptation Fund, which is set up under the Kyoto Protocol and funded through a levy on most Clean Development Mechanism (CDM) projects, is of particular importance to

developing countries as it is pioneering the direct access mechanism which allows countries to access funds without having to work through a multilateral development agency. The direct access mechanism highlights the role of institutions in building and maintaining capacity, not just in the technical aspects of adaptation assessment and project design, but also in financial management and due diligence (Brown et al., 2011).

Effective governance is important for efficient operations of institutions. In general, governance rests on the promotion of democratic and participatory principles as well as on ensuring access to information, knowledge, and networks. Institutional strengthening and capacity building has been highlighted as a priority need in developing countries (Kumamoto and Mills, 2012). In assessment of river basin planning in Brazil, Engle and Lemos (2010) found that improving governance mechanisms appears to enhance adaptive capacity. Similarly water-trading schemes facilitated by new government measures reduced the impact of a major drought on the economy in Australia (Mallawaarachchi and Foster, 2009). The effectiveness of such approaches depends on both government will and capacity building among those affected.

In terms of national or local adaptation planning and policy making, Chapter 15 emphasizes that it can be challenging for governments to move beyond adaptation planning to implementation (Section 15.2.2). In an evaluation of one of the earliest national adaptation strategies for Finland, it was found that few measures had been implemented except in the water sector (see Box 23-2). Adaptation planning can occur at a number of spatial scales including at the national, regional, city, district, or local community level. Action plans can include a range of adaptation options including structural, social, and regulatory measures. For example, the city of Quito has proposed developing dams, encouraging a culture of rational water use, reducing water losses, and developing mechanisms to reduce water conflicts (Section 8.3.3.4). Table 25-5 lists various urban climate change adaptation options and their barriers to adoption. See also Section 15.3 on local adaptation plans.

Institutional adaptation options include the use of various decision-making and adaptation planning tools (Chapter 15) including iterative risk management (Chapter 2). There are various decision-making paradigms that can guide adaptation actions. For example, prominent institutional frameworks used for management of coastal areas include Integrated Coastal Zone Management (ICZM) and Adaptive Management (see Section 5.5.1.4). At the local scale, community-based adaptation refers to the generation and implementation of locally driven adaptation strategies through a learning-by-doing, bottom-up approach (Section 5.5.1.4). Community-based approaches to adaptation can also be mainstreamed into local or regional plans. Refer to Table 5-4 for a description of community-based adaptation options for coastal areas.

14.3.4. Selecting Adaptation Options

Selecting specific adaptation options can be challenging partly due to the rate, uncertainty, and cumulative impacts of climate change. How adaptation is framed will have an impact on how adaptation options are selected (Fünfgeld and McEvoy, 2011). Policy and market conditions may be a stronger driver of behavior than the observed climate itself (Berkhout et al., 2006). Also, rarely will adaptation options be designed to address climate risks or opportunities alone (IPCC, 2007b); instead actions will often be undertaken with other goals (such as profit or poverty reduction) in mind, while also achieving climate-related co-benefits. Gains in reduced vulnerability, enhanced resilience, or greater welfare will often be co-benefits generated as a result of changes and innovations driven by other factors (Khan et al., 2013). Rather than focusing on adaptation options addressing specific dimensions of climate change, more attention is being paid to mainstreaming climate change into wider government policy and private sector activities (see Sections 15.2.1, 15.5.1; Sietz et al., 2011a).

Selection and prioritization of adaptation options is important because not all adaptation options will be possible owing to constraints such as insufficient local resources, capacities, and authority (see Section 16.7). Furthermore, some adaptation options can be maladaptive if they foreclose other options (see Section 14.7). The viability of adaptation options is dependent on the time scale and climate scenario, emphasizing that selecting adaptation options is an iterative process.

A variety of systematic techniques have been developed for selecting options (e.g., see Section 15.4; De Bruin et al., 2009; Füssel, 2009; Ogden and Innes, 2009). Quantification and other systematic approaches to selecting options have many virtues. However, they also have limitations. For instance, most of these methodologies do not account for a range of critical factors such as leadership, institutions, resources, and barriers (Smith et al., 2009). For example, cost-benefit analysis of adaptation options requires valuation of non-market costs and benefits, which can be impractical (Section 17.3.2). Strategies dominating the early adaptation literature emphasized maintaining the current system and minimizing costs while achieving some form of benefit. For instance, no-regrets measures both reduce climate risk and provide other social, economic, or environmental benefits (Hallegatte, 2009). Risk management approaches often lead to no-regrets, low-regrets, or win-win options, while multi-criteria analysis (MCA) allows assessment of options against different criteria, as was used in the preparation of NAPAs (UNFCCC, 2011).

As ideas about adaptation have evolved, there has been a shift in ambition from traditional approaches that emphasize maintaining the status quo to more dynamic and integrative strategies (see also Sections 2.4.3, 14.1, 16.4.2, 20.5). Adaptive management places an emphasis on taking action and then using the lessons learned to inform future actions in order to make better informed, and often incremental, decisions in the face of uncertainty (Sections 2.2.1.3, 14.4). Lempert and Schlesinger (2000) have proposed that adaptation options should be robust against a wide range of plausible climate and societal change futures. Emerging trends in adaptation place an emphasis on the need for more transformational changes, which has a distinct logic that differs from traditional strategies (see Section 14.1).

As research and experience in the practice of adaptation grows, an ever increasing number of considerations have been advanced as being important in guiding the selection and sequencing of adaptation options. It is unlikely that every adaptation program can ever fully meet each of these considerations, especially as they are increasingly integrated with

Table 14-2 | Considerations when selecting adaptation options.

Consideration	Source (section) within this volume and selected references
Effective in reducing vulnerability and increasing resilience	9.3.5, 11.3; UNFCCC (2007); Brooks et al. (2011)
Efficient (increase benefits and reduce costs)	17.2, 17.4; Stern (2006); IFC (2010)
Equitable, especially to vulnerable groups	Chapter 12; 13.2.1; Huq and Khan (2006)
Mainstreamed/integrated with broader social goals, programs, and activities	15.1, 15.5; Agrawala (2005); Dowlatabadi (2007); Swart and Raes (2007); Agrawala and van Aalst (2008); Ayers and Dodman (2010)
Stakeholder participation, engagement, and support	12.3.1, 13.3, 15.1, 15.2; Swart and Raes (2007)
Consistent with social norms and traditions	12.3.1, 13.1.2; Moser (2006); O'Brien et al. (2007); Alexander et al. (2011)
Legitimacy and social acceptability	20.3.2; UNFCCC (2007); Brooks et al. (2011)
Sustainable (environmental and institutional sustainability)	13.1, 15.3; Brooks et al. (2007); Brown et al. (2011)
Flexible and responsive to feedback and learning	2.3.2, 2.3.3, 16.3, 20.2.3.2; Suarez et al. (2009); Agrawal (2010)
Designed for an appropriate scope and time frame	15.2.3.2, 16.1; Preston and Stafford-Smith (2009); Stafford-Smith et al. (2010); Brown et al. (2012)
Likely to avoid maladaptive traps	14.6; Grothmann and Patt (2005); Repetto (2008)
Robust against a wide range of climate and social scenarios	2.1.1, 17.2.5, 17.3.2; Lempert and Schlesinger (2000); Carmin and Dodman (2013)
Resources available (including information, finance, leadership, management capacity)	14.2.4; UNFCCC (2007); Martens et al. (2009); Brooks et al. (2011); Webb and Beh (2013)
Need for transformative changes considered	14.1; Wilbanks and Kates (2010); Park et al. (2012)
Coherence and synergy with other objectives, such as mitigation	14.6; Klein et al. (2007); UNFCCC (2007); Barnett and O'Neill (2010)

wider social or development goals, but Table 14-2 seeks to outline the most common considerations and point to sources in this volume and the literature for a discussion of some of the core issues.

14.4. Adaptation Assessments

14.4.1. Purpose of Assessments

Identifying adaptation needs requires an assessment of the factors that determine the nature of, and vulnerability to, climate risks (climate change assessments, climate impacts and risk assessments, and vulnerability assessments) and an assessment of adaptation options to reduce risks (adaptation assessment). The various types of climate change assessments differ in that they pursue different goals, are underpinned by different theoretical frameworks, and rely on different forms of data and ultimately may lead to different adaptation responses (Fünfgeld and McEvoy, 2011).

Assessments help decision makers understand the impacts, vulnerability, and adaptation options in a region, country, community, or sector. They are often characterized into "top-down" and "bottom-up" assessments. Top-down assessments are used to measure the potential impacts of climate change using a scenario and modeling driven approach. Bottom-up assessments begin at the local scale, address socioeconomic responses to climate, and tend to be location specific (Dessai and Hulme, 2004). They are often used to determine the vulnerability of different groups to current and/or future climate change and their adaptation options, using stakeholder intervention and analyzing socioeconomic conditions and livelihoods (UNFCCC, 2010). There are also policy-based assessments, which assess current policy and plans for their effectiveness under climate change within a risk-management framework (UNDP, 2004, 2005). The evolution of assessments has led to a more thorough assessment of society's ability to respond to risks through various adaptations, which can help guide allocation of adaptation resources (Füssel and Klein, 2006). In practice assessments have become increasingly complex, often combining elements of top-down and bottom-up approaches (e.g., Dessai et al., 2005). Decision makers use both in the policy process (Kates and Wilbanks, 2003; McKenzie Hedger et al., 2006).

14.4.2. Trends in Assessments

A variety of frameworks have been developed for the assessment of climate impacts, vulnerability, and adaptation (Fünfgeld and McEvoy, 2011). "Impacts-based" approaches focus primarily on the biophysical climate change impacts to which people and systems need to adapt. "Vulnerability-based" approaches focus on the risks themselves by concentrating on the propensity to be harmed, then seeking to maximize potential benefits and minimize or reverse potential losses (Adger, 2006; IPCC, 2007b). "Adaptation-based" approaches examine the adaptive capacity and adaptation measures required to improve the resilience or robustness of a system exposed to climate change (Smit and Wandel, 2006). In practice these approaches are interrelated, especially with regard to adaptive capacity (O'Brien et al., 2007). An evolution in the conceptualization of risk and vulnerability in the past decade has led to more holistic and integrated approaches to assessment, aiming toward a more systemic understanding of the complexity of human-environment interactions (Preston et al., 2011b).

The "standard approach" to assessment has been the climate scenario-driven impacts-based approach, which developed from the seven-step assessment framework of the IPCC (Carter et al., 1994; Parry and Carter, 1998): (1) define the problem (including study area and sectors to be examined), (2) select method of problem assessment, (3) test methods/conduct sensitivity analyses, (4) select and apply climate change scenarios, (5) assess biophysical and socioeconomic impacts, (6) assess autonomous adjustments, and (7) evaluate adaptation strategies. This approach dominated the assessment sections of the first three IPCC reports, and aims to evaluate the impacts of climate change under a given scenario and to assess the need for adaptation and/or mitigation

to reduce any resulting vulnerability to climate risks (IPCC, 2007a). These frameworks are described as "first generation" or "type 1" assessment studies (Burton et al., 2002). The standard impact approach is often described as top-down because it combines scenarios downscaled from global climate models to the local scale with a sequence of analytical steps that begin with the climate system and move through biophysical impacts toward socioeconomic assessment (IPCC, 2007b). The process of downscaling of global climate models leads to issues of uncertainty and limited statistical confidence (Fünfgeld and McEvoy, 2011).

A new generation of scenario-based impact assessments has also emerged linking biophysical, economic, and social analysis tools. Refer to Section 2.3.2 for examples of large-scale and regional-scale scenario-based vulnerability assessments that have taken place linking biophysical and socioeconomic futures. In Europe, a study by Ciscar et al. (2011) estimated economic welfare losses over four sectors of 0.2 to 1% by the 2080s (Section 2.3.2.1). In Australia, socioeconomic considerations are beginning to be used to inform assessments of adaptive capacity and vulnerability (Section 25.3.2). A risk-based framework, based on the risk management approach, can also be used for assessing adaptation opportunities, constraints, and limits (Section 16.2). Economic assessments are also used to estimate the impacts of climate change, including distributional impacts and adaptation costs and benefits (Chapter 17).

The "second generation" vulnerability and adaptation assessments (Burton et al., 2002) pay greater attention to information around vulnerability to inform decisions on adaptation. They are characterized by the intensive involvement of stakeholders and the participation of vulnerable groups in decision making around adaptation options (Füssel and Klein, 2006; LDC Expert Group, 2012). Local projects often use participatory vulnerability assessment (PVA) methods. In Bangladesh, community-based adaptation has combined consensus-building and participatory rural appraisal (PRA) to assess needs of the communities and propose adaptation actions (Section 15.2.1). In activities by CARE, vulnerability assessments were undertaken with men and women's groups separately to ensure activities were gender sensitive (see Section 7.5.2). Participatory vulnerability assessments offer an opportunity to avoid maladaptation by involving stakeholders, for example, in a vulnerability assessment of tourism in the Mamanuca Islands in Fiji, where stakeholders were explicitly integrated into each step of the process (Section 29.8).

Adaptation assessments continue to evolve, but most syntheses now include "top-down" and "bottom-up" approaches, and include the assessment of both biophysical climate change risks and the factors that make people vulnerable to those risks. There is a shift toward integrating community-based planning into national adaptation plans. The Government of Nepal proposes "LAPA assessments" (Local Adaptation Plans of Action) that seek to integrate top-down and bottom-up models (Government of Nepal, 2011). There is also increasing attention to institutional capacity assessments and policy environments as key factors that can both drive vulnerability and also determine the type and success of different adaptation options. The generic elements of adaptation and vulnerability assessment are reflected in the the UK Climate Impacts Program (UKCIP) guidelines presented in Figure 14-2.

14.4.3. Issues and Tensions in the Use of Assessments

Adaptation and risk assessments give rise to various tensions, three of which are discussed here. The first is the adaptation paradox, which recognizes that climate change is a global problem while vulnerability

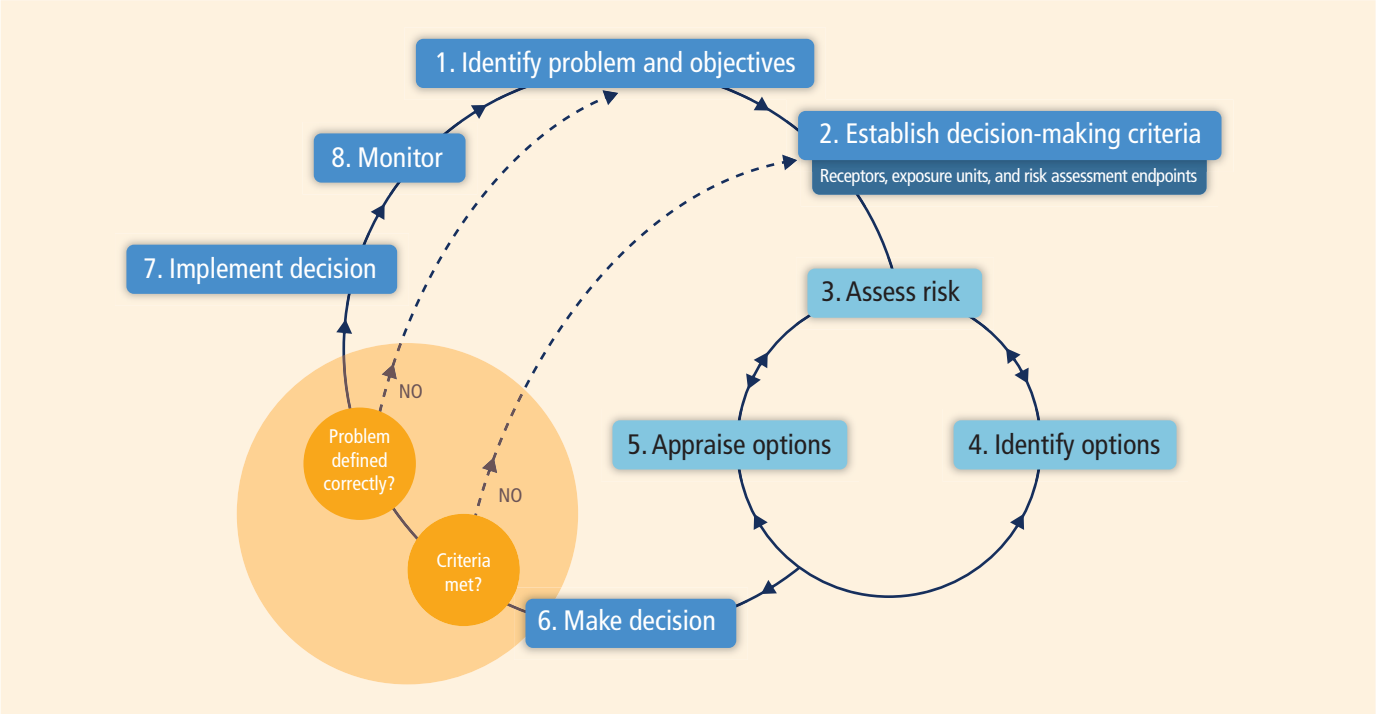

Figure 14-2 | A generic framework for vulnerability and adaptation assessments (UKCIP, 2011).

is locally experienced (Ayers, 2011). Top-down assessments of climate scenarios are deemed necessary in order to understand the climate change scenarios that render climate risk. However, the factors that make people vulnerable to climate risks are often locally generated, so require locally driven bottom-up analysis, while factors at the national and regional levels also determine vulnerabilities. Bottom-up analysis tends to prioritize groups based on factors related to poverty and development that drive vulnerability. Top-down assessments tend to prioritize those most exposed to climate risks. Analysis in Nepal that assessed both under-development and climate change impacts showed that, at the household scale, there was a strong correlation between local measures of poverty and vulnerability to climate change (Ghimire et al., 2010). However, when indicators were aggregated at district scale, the correlation was weaker—even when the vulnerability index used included poverty as a proxy for adaptive capacity alongside climate hazard risk and exposure (Ghimire et al., 2010).

There are also tensions around ownership and participation. Assessments managed under global climate change governance structure of the UN Framework Convention on Climate Change are developed under an "impacts-based" paradigm (Burton et al., 2002). This impacts-based approach requires external scientific and technological expertise for defining climate change problems, and formulating technological adaptation solutions, based on specific knowledge of future climate conditions. Such assessments are necessarily "top-down" because this expertise exists at the global and national level. At the local level, the capacity to adapt is based on the underlying securities that determine vulnerability to these impacts in the first place (Adger et al., 2003a). Accessing this information requires "bottom-up" and participatory assessments that engage local vulnerable people. These vulnerable groups and institutions often do not have access to the climate impacts science necessary to fully apply top-down impacts-based assessments. Some places also do not have accurate historical weather data, making it difficult to validate climate trends and models and hence develop evidence-based scenarios of what will happen with any degree of accuracy (Conway, 2009).

The numerous assessments that have been carried out have led to increased awareness among decision makers and stakeholders of climate risks and adaptation needs and options. But this awareness is often not translated into the implementation of even simple adaptation measures within ongoing activities or within risk management planning. There is a bottleneck in adaptation assessments, which may need to be overcome by linking more directly to particular decisions and tailoring the information to local contexts to facilitate the decision-making process (Preston and Stafford Smith, 2009; Brown et al., 2011). Specific techniques such as decision scaling, which seeks to understand which climate conditions would result in hazardous conditions of concern for particular stakeholder groups, are a step in this direction (Brown et al., 2012; Moody and Brown, 2012). Decision support must recognize that human psychological dimensions play a crucial role in the way people perceive risks and make decisions (Section 2.2.1.2). Impacts and adaptation options will also have to be successfully communicated to the local scale. One example of this is local-scale visualization of impacts and adaptation measures, as has taken place in British Columbia, Canada (see Section 2.2.1.3). Use of ICT tools can foster new ways to assimilate or translate information (see Box 15-1). Vulnerability mapping, including the use of geographic information systems (GIS), can help stakeholders to visualize the impacts of climate change on the landscape, while integration with participatory processes can facilitate learning and deliberation (Preston et al., 2011a).

14.4.4. National Assessments

Under the UNFCCC, all parties are encouraged (Annex 1 countries are required) to report on activities in relation to "vulnerability assessment, climate change impacts and adaptation measures" (FCCC/CP/1999/7). Parties are encouraged to use the IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations (Carter et al., 1994) and the UNEP Handbook on Methods for Climate Change Impacts Assessment and Adaptation Strategies, which focuses on the impacts of sea level rise and uses the seven-step assessment framework (described previously). Annex 1 countries are due to submit their sixth Communications by 2014 and most non-Annex I countries are due to have submitted at least one Communication; some are on their fifth. As such, National Communications have formed the first avenue for assessing and reporting on climate risk and vulnerability assessments at the national level. Most initial National Communications to the UNFCCC produced by developing countries were first-generation vulnerability assessments, which did not seek to assess the feasibility of implementing adaptations (Füssel and Klein, 2006). Undertaking such assessment is resource intensive, underscoring the need for further resources, training, and expertise.

There is a range of emerging national experiences on adaptation and vulnerability assessments. For coastal areas under sea level rise, a summary of the results from coastal vulnerability assessments is shown in Table 5-5. Such assessments show that vulnerability is highly dependent on the greenhouse gas (GHG) mitigation scenario. In Kenya, a study by the Stockholm Environment Institute (SEI) estimated the economics of climate change under a range of scenarios (see Figure 22-6) and estimated that, by 2050, more than 300,000 people could be flooded per year under a high-emissions scenario. In 2012, the UK's first Climate Change Risk Assessment (CCRA) was undertaken based on a similar framework to that shown in Figure 14-2, to assess risks in and across eleven sectors to inform priorities for action and appropriate adaptation measures (DEFRA, 2012).

National Adaptation Programmes of Action are designed as a vehicle for Least Developed Countries (LDCs) to communicate their most "urgent and immediate adaptation needs" to the UNFCCC for funding from the Least Developed Countries Fund (LDCF). "Urgent and immediate needs" are defined as those for which further delay in implementation would increase vulnerability or increase adaptation costs at a later stage (LDC Expert Group, 2009). The approaches adopted for vulnerability assessment under NAPAs vary. Although the guidelines call for more participatory and "bottom-up" mechanisms to be adopted, time and funding limitations have meant that often the NAPA process remains largely top-down, focused on impacts and consulting the communities only to verify this information (Huq and Khan, 2006; Ayers, 2011). Moreover, available financial resources were too limited to fully assess and address the needs of all sectors and all vulnerable regions of the country (LDC Expert Group, 2012; see also Section 15.2.1.2).

Frequently Asked Questions

FAQ 14.1 | Why do the precise definitions about adaptation activities matter?

Humans have always adapted to changing conditions: personal, social, economic, and climatic. The rapid rate of climate change now means that many groups, ranging from communities to parliaments, now have to factor climate change into their deliberations and decision making more than ever before. Having a term and working definition is always useful in discussing how to tackle a challenge as it helps define scope. Is adaptation all about minimizing damage or are there opportunities as well? Can adaptation proceed only through deliberately planned actions focused specifically on adaptation to climate change? How much must be known about future climates to make decisions about adaptation? How does the adaptation of humans systems differ from adaptation in natural systems? Can adaptation to climate change be distinguished from normal development and planning processes? Need it be? Are we adequately adapted to current climates, or do we have an "adaptation deficit"? The phrase "maladaptation" immediately turns thoughts to how could plans go wrong and possibly cause greater suffering. A definition does not answer all these questions but it provides a framework for discussing them.

There is also a political reason for needing a precise definition of adaptation. Developed countries have agreed to bear the adaptation costs of developing countries to human-induced climate change and that these funds should represent "new and additional resources,"[4] and the Cancun Agreement and subsequent discussions suggest that for adaptation these funds could amount to tens of billions US$ per year.[5] In most cases adaptation is best carried out when integrated with wider planning goals such as improved water allocation, more reliable transport systems, and so forth. How much of the cost of upgrading a coastal road that is already subject to frequent damage from bad weather should be attributed to normal development and how much to adaptation to climate change? A precise answer may never be possible but the closer we agree as to what constitutes adaptation, the easier it will be to come to workable agreements.

Under the Cancun Adaptation Framework (CAF), a process was established to enable LDC parties to formulate and implement National Adaptation Plans (NAPs). NAPs are intended to build on NAPAs but shift the focus toward identifying medium- and long-term adaptation needs and developing and implementing strategies and programs to address those needs. NAPs are intended to facilitate the integration of climate change adaptation into relevant national and subnational development and sectoral planning (LDC Expert Group, 2012). Other developing country parties are also invited to employ the modalities formulated to support the national adaptation plans in the elaboration of their planning efforts. Early guidelines (LDC Expert Group, 2009) propose a country-specific approach tailored to national circumstances, mixing top-down policy-first assessments with bottom-up approaches. Recent guidelines propose that this should be non-prescriptive and should facilitate country-driven, gender-sensitive, participatory action, taking into consideration vulnerable groups, communities, and ecosystems (LDC Expert Group, 2012). Refer also to Sections 2.4.3 and 15.2.1.2 for further details of national and subnational adaptation planning including NAPAs and NAPs.

14.5. Measuring Adaptation

Adaptation has tended to lag behind mitigation efforts both in research and in the climate negotiations. In part this is because adaptation and development specialists, governments, NGOs, and international agencies have found it difficult to clearly define and identify precisely what constitutes adaptation, how to track its implementation and effectiveness, and how to distinguish it from effective development (Burton et al., 2002; Arnell, 2009; Doria et al., 2009). A contributing reason is that adaptation has no common reference metrics in the same way that tonnes of GHGs or radiative forcing values are for mitigation. This section seeks to explore the feasibility of finding metrics for measuring adaptation effectiveness.

The search for metrics[6] for adaptation will remain contentious, with many alternative uses competing for attention. This is inevitable as there are multiple purposes and viewpoints in approaching the measurement of adaptation (Hulme, 2009). Brooks et al. (2011) asked "what constitutes successful adaptation" and suggested that the criteria by which success

[4] Bali Action Plan, 2007; FCCC/CP/2007/6/Add.1.

[5] Cancun Agreements 2010, FCCC/CP/2010/7/Add.1, paras 98 & 102.

[6] There is no consistent use of the terms metric, measure, and indicator in the literature. Here we try to stay as close as possible to the dictionary meanings (although they overlap). A measure is the amount or degree of something, that is, a description of its (presumably current) state. A metric is often a group of values (measures) that taken together give a broader indication of the state or the degree of progress to some desired state. An indicator is a sign, or estimate of the state of something and often of the future state of something. Most often in seeking to understand the state of vulnerability or adaptation, etc., we need a metric (i.e., a group of measures) and we use the term in that way. In describing the components of a metric we will give preference to the term indicator over measure.

might be assessed include feasibility, efficacy/effectiveness, efficiency, acceptability/legitimacy, and equity (derived from Yohe and Tol, 2001; Adger et al., 2005; Stern, 2006), to which they added sustainability (Fankhauser and Burton, 2011). Effective integration and coherence with wider national policies and development goals is another often sought criterion (World Bank, 2010). Also institutions, communities, and individuals value things differently and many of those values cannot be captured in a comparable way within metrics (Adger and Barnett, 2009).

At least three uses of metrics for adaptation are relevant, each requiring different characteristics of the indicators used. The first use seeks metrics to help determine the need or determinates of that need for adaptation. These metrics usually focus on measuring vulnerability, but that term is not well defined. For example, Hinkel (2011) identifies six uses that vulnerability indicators are sometimes expected to serve and concludes that they can truly serve only their core purpose, that is, to identify vulnerable people, communities, and regions. Further, even with metrics focusing on vulnerability the goal often is not to produce a score or rating to identify vulnerable groups but to elucidate information on the nature of vulnerability and to better identify adaptation options (Smit and Wandel, 2006; Sietz et al., 2011b). The second use of metrics relates to measuring and tracking the process of implementing adaptive actions, such as spending on coastal protection, the number of early warning plans implemented as part of a program, or the number of agricultural specialists with appropriate training in climate risks. Here the selection of appropriate metrics is usually less contentious but there is disagreement as to how much they capture adaptation rather than normal development. The third use of metrics relates to measuring the effectiveness of adaptation such as in monitoring and evaluation. This set is essential to help measure progress and provide feedback on the effectiveness of actions, but is among the most difficult to identify as adaption outcomes take time to become identifiable and are often subject to evolving conditions and objectives.

14.5.1. What Is to Be Measured?

The measurement of vulnerability is central to many adaptation metrics and initially it was approached from an impacts point of view. Here vulnerability is usually defined as a function of (1) exposure to specific hazards or stressors, (2) sensitivity to their impacts, and (3) the target population's capacity to adapt (IPCC, 2001, Chapter 17). This approach continues to be used as the basis of many assessments and adaptation prioritization efforts. Recently the emphasis has moved from better defining exposure and potential impacts to a better understanding of the factors that affect societies' sensitivity to those impacts and their capacity to adapt. This reflects the increasing recognition of the importance of considering social vulnerability alongside biophysical vulnerability. Various terms have been used to describe these different emphases including biophysical versus social vulnerability, outcome versus contextual vulnerability (Section 14.2.1.1; Eakin and Luers, 2006; Füssel and Klein, 2006; Eriksen and Kelly, 2007; Füssel, 2010), and scientific framing versus a human-security framing of vulnerability (O'Brien, 2007). O'Brien et al. (2007) argue that scientific and human-security frameworks affect the way we approach adaptation, with the scientific framework leading to building local and sectoral capacity to make changes rather than address the fundamental causes of vulnerability, or climate change itself, within their broader geopolitical and economic contexts.

Other questions also arise even within a given conceptual framework for considering vulnerability. A system of measurement is usually developed to allow comparisons between different places, social groups, or sectors of activity, although experience repeatedly cautions us to be careful in doing so (Schröter et al., 2005). The challenge is as much of integration across widely differing research domains and traditions (Polksy et al., 2007). Also, a system's vulnerability is not static but can respond rapidly to changes in economic, social, political, and institutional conditions over time (Smit and Pilifosova, 2003; Smit and Wandel, 2006). Much of the effort in relation to estimating social vulnerability is reviewed in Cutter et al. (2009).

It has also been suggested that a framework based on the concept of resilience is more appropriate than a vulnerability framework in many contexts (see IPCC, 2012, Chapter 2 and Section 8.3.3 for more details). For example, in a development context resilience "evokes positive and broad development goals (e.g., education, livelihood improvements, food security), includes multiple scales (temporal and spatial) and objectives, better captures the complex interactions between human societies and their environments, and emphasizes learning and feedbacks" (Berkes, 2007; Moss et al., 2012, p. 6). A resilience approach also leads to more focus on interactions between social and biophysical systems (Nelson et al., 2007). However, others feel that resilience promotes too great a focus on the return of the overall system to pre-impact conditions and not enough on the human agents and their need to adapt to changing conditions (Nelson et al., 2007; IPCC, 2012, Section 8.3.3). The concept of resilience has been difficult to apply in practice and is particularly resistant to attempts to establish commonly accepted sets of indicators. Some (e.g., Klein et al., 2003) have suggested that resilience has become an umbrella concept that has not been able to support effectively planning or management.

Recently Brooks et al. (2011) have outlined a framework tracking adaptation that combines the establishment of upstream metrics to assess how well risks are being managed by institutions, and downstream metrics to track whether the interventions are reducing the vulnerability of affected groups. The upstream metrics would focus on assessments of institutional capacity, managerial performance, and integration of climate risk management into planning processes and tracking and feedback processes. The downstream metrics would focus on indicators to track development performance and changes in vulnerability. Attribution of these changes to particular interventions would be desirable but not essential to track progress.

But understanding vulnerability does not necessarily translate to effective adaptation. Smit et al. (2001), Osman-Elasha et al. (2009), and others have suggested that the focus should be on increasing adaptive capacity within the context of the full range of biophysical and socioeconomic stressors. However, as the scope of the metrics is widened to include aspects of development and sustainability they often become less suitable for other purposes such as helping to identify "the full and additional costs of adaptation" (McGray et al., 2007). In deriving indices of vulnerability there are again several broadly different approaches. One is to deductively identify indicators that theoretically should be strongly

Table 14-3 | Criteria for the selection of indicators (based on multiple sources).

Criterion		Explanation
Validity	Not ambiguous	Agreement on the direction of influence between the indicator and what is sought to be measured (target measure)
	Well founded	Based on a tested theoretical framework
	Well defined	So that unwitting errors are minimized (e.g., measuring a family or a household)
	Purpose known	This helps fix problems in data collection; misunderstandings between different collecting agencies, etc.
	Accurate	Measuring what it should, and responds quickly
	Precise	Statistical variation between measurements is low
	Quality checked	Ideally subject to independent checking; is there a cross checking mechanism?
	Transparent	Information source and control of information flow is known
	Honest	There should be no rationale or opportunity for individuals to manipulate or distort the data (e.g., manipulating rain-gauges used for weather index insurance)
Value	Comprehensible	Relatively easy for user to understand
	Relevant	Applicable to a wide range of circumstances (geographic, social, economic)t
	Responsive	Can measure usefully small changes in the target measure
	Actionable	The quality/quantity of what is being measured can be affected by human appropriate actionst
	High information content	Usually quantitative is more useful than qualitative, than binary data; and real measurements more useful than modeled estimates or expert judgment
	Disaggregatable	Can the indicator be collected for specific groups (e.g. children, women, and men)
	Participatory	Can local people be involved in the data collecting; does the data help inform and possibly empower them
Data	Available	Data is publicly and easily available; affordable
	Homogenous	Data collection is consistent across location and time, including matching season or time-of-day if necessary
	Periodic	Data is collected at a frequency that is suitable for tracking changes
	Long time course	Data has been consistently collected for some years
	Spatial coverage	Spatial coverage must be sufficient to provide a fair representation of the measure (e.g. density of rain gauges)

related to vulnerability (e.g., Dolan and Walker, 2003; Polsky et al., 2007), while the other is inductive and uses observed data to seek correlations between indicators and observed consequences of vulnerability, such as the number of people killed or affected by climate-related events in recent history. There is some commonality in identifying the desirable criteria for selecting indicators, and though no list can ever be complete, Table 14-3, based initially on Perch-Nielsen (2010), seeks to bring together some of the most common criteria.

14.5.2. Established Metrics

Numerous metrics continue to be prepared for a variety of purposes and at scales ranging from estimating the vulnerability of individuals and communities to comparing countries. Several reviews, including Moss (2001, 2012), Srinivasan and Prabhakar (2009), and Prabhakar and Srinivasan (2011), discuss both the design and effectiveness of many of the existing proposals for adaptation metrics.

14.5.2.1. Vulnerability Metrics

Eriksen and Kelly (2007) found strong divergence among five metrics (or indices) for comparing national vulnerability published over the period 1995–2003: the Dimensions of Vulnerability of Downing et al. (1995); the Index of Human Insecurity (IHI) of Lonergan et al. (1999); the Vulnerability-Resilience Indicators of Moss et al. (2001); the Environmental Sustainability Index of the World Economic Forum (2002); and the Country-Level Risk Measures of Brooks and Adger (2003). Between them, 29 indicators were used, with only five indicators appearing in more than one study. They were able to compare the 20 countries ranked as most vulnerable from three of the studies and found little overlap, with only five countries ranked in the top 20 in more than one study. However, it must be noted that the metrics were developed at different times and for different purposes. They concluded that the indices focused on measuring a snapshot of aggregate conditions rather than on delivering guidance on societal processes that can be targeted to reduce vulnerability.

There are a series of disaster-related indices designed to assess relative risks across countries and regions, and to provide benchmarks on which to assess progress. Among them are the Disaster Risk Index (UNDP, 2004); Hotspots Index (Dilley et al., 2005); the Americas Index (Cardona, 2005); and an index for South Asia (Moench et al., 2009). Again, there has been little effort to further analyze, validate, or compare these metrics.

14.5.2.2. Metrics for Resource Allocation

Vulnerability indices have usually been selected to better understand the drivers of vulnerability or to compare countries, regions, communities, and so forth in terms of the risks they face from climate change and their capacity to deal with them. This is not necessarily the same as designing an allocation index or rule to be used to allocate limited resources equitably and efficiently among entities (countries, regions or other administrative groups, or different proponents of adaptation). For allocation, vulnerability and coping/adaptive capacity might be

expected to remain a core consideration, but so also should the relative costs of implementation in relation to the potential benefits and the ability of the recipients to absorb the funding and implement policies and projects to actually achieve the projected benefits (UNFCCC, 2007; Parry et al., 2009; Wheeler, 2011).

One of the longest running and prominent uses of metrics in funding is the World Bank's process of allocating IDA concessional funds to developing countries, which faces many issues analogous to the same process for adaptation. The World Bank uses the Country Policy and Institutional Assessment (CPIA) based on 16 criteria, many qualitative, to estimate the extent to which a country's policy and institutional framework supports sustainable growth and poverty reduction, and consequently the effective use of development assistance. These criteria are the main components used to calculate a Country Performance Rating, which in turn is a major component, along with population and recent performance measures, in calculating allocations to the poorest developing countries with long-term, no interest (IDA) loans. The CPIA and the ultimate IDA allocation formulae are controversial, much debated (Alexander, 2010), and often fine-tuned (IEG, 2009) but still commonly used as a reference point for this type of procedure (GTZ, 2008).

An explicit example of the use, and non-use, of adaptation metrics was in establishment of the Pilot Program for Climate Resilience (PPCR). The governing body, made up of contributors, recipients, and other stakeholders, set up an independent expert group to make recommendations as to which countries might be included as pilots within the approximately US$1 billion program (Climate Investment Funds, 2009). The expert group refrained from using a simple index, but instead country selection was done across nine regions and each based on a suite of indicators appropriate for the region using expert judgment. It is interesting to note that on moving to the next step of deciding on allocation of financial resources to the selected pilot countries the governing body of the PPCR chose not to use an approach based on indicators, but to provide guidance to the countries of the possible range of funding and to base allocations on the quality of the proposals brought forward (Climate Investment Funds, 2009). Similarly, none of the other governing bodies of international adaptation funding mechanisms (e.g., the Global Environment Facility, the Adaptation Fund) has chosen to use a defined set of metrics within their decision making.

Wheeler (2011) has developed an index of vulnerability based on weather-related disasters, sea level rise, and agricultural productivity. The index can be adjusted according to user preferences to develop allocation formulas based only on biophysical vulnerability, further adjusted for economic development and governance, and finally for project costs and probability of success. Klein and Möhner (2011) have discussed the options for the Green Climate Fund based on experience to date and conclude that science cannot be relied on for a single objective ranking of vulnerability.

14.5.2.3. Metrics for Monitoring and Evaluation

The IPCC's Fourth Assessment Report provided little discussion of the role of evaluation and monitoring of adaptation responses as a component of building adaptive capacity (Adger et al., 2007). Preston et al. (2011a) identify three specific roles of evaluation: (1) ensuring reduction in societal and ecological vulnerability, (2) facilitating learning and adaptive management, and (3) providing accountability for adaptation investments (see also GIZ, 2011). A central challenge in developing robust monitoring and evaluation frameworks for adaptation is the existence of multiple, valid points of view that can be used to evaluate adaptation actions and their continuing effectiveness (Gagnon-Lebrun and Agrawala, 2006; Perkins et al., 2007; Füssel, 2008; Smith et al., 2009; Ford et al., 2011; Preston et al., 2011b). This challenges the selection of appropriate metrics for the monitoring and evaluation of adaptation and its contribution to vulnerability reduction (Burton and May, 2004; Gagnon-Lebrun and Agrawala, 2007; McKenzie Hedger et al., 2008; Ford et al., 2011).

One of the central unresolved tensions in progressing evaluation is the relative merit of comparatively easy and objective targeting of the completion of the processes and outputs needed to implement an adaptation program versus the outcomes, such as changes in livelihoods or reduction in risks. Assessment of outcomes is less objective, subject to whether appropriate circumstances occur (e.g., that floods occur so that risk reduction can be demonstrated) and usually take much longer to establish. Preston et al. (2011b) suggest the evaluation of adaptation processes may be a more robust approach to evaluation, owing to the difficulties in attributing future outcomes to adaptation strategies and the long-time lags that may be needed to assess the performance of a particular strategy (Berkhout, 2005; Dovers and Hezri, 2010; Ford et al., 2011). The OECD analyzed the monitoring and evaluation processes across 106 adaptation projects across six development agencies and found that Results Based Management and Logical Framework approaches dominated, as they do in normal development projects (Lamhauge et al., 2011). They also drew attention to the need for appropriate baselines and complementary sets of indicators that track not just process and implementation, but also the extent to which targeted changes are occurring. Monitoring programs themselves will need careful design to ensure that they remain in place over the long time frames needed for the outcomes to be identified; that they contain incentives for beneficiaries to comply with conditions; and that compliance itself does not impose undue burdens.

A number of national and international organizations have guides to monitoring and evaluating adaptation activities (McKenzie Hedger et al., 2008; UNDP, 2008; WRI, 2009; World Bank, 2010; GIZ, 2011). These guides tend to focus on the wider framework of identifying and managing adaptation-related activities and within that the criteria for the selection of metrics for monitoring and evaluating those activities. These issues are dealt with in Chapters 15 and 16.

14.5.3. Validation of Metrics

The practice of developing and applying metrics in adaptation has been subject to much scrutiny. Eakin and Luers (2006) express serious concerns about national-scale vulnerability assessments ranging from the quality of the available data, the selection and creation of indicators, the assumptions used in weighting of variables, and the mathematics of aggregation. Nevertheless metrics will continue to be used and the challenge is to identify and maintain basic standards of best practice.

One of the most comprehensive attempts to validate a system for measuring important components of adaptation is that of Brooks et al. (2005). They used the probability of national climate-related mortality from the CRED database of climate-related disasters[7] as a proxy for risk and selected a set of 46 social, governance, economic, and biophysical measures as indicators of social vulnerability. They found that 11 were effective indicators of mortality rates and these were confirmed as useful by a small focus group of seven adaptation experts. These experts also ranked the variables in terms of their perception of their usefulness leading to a total of 12 different rankings to which was added an equal ranked set to give 13 measures of vulnerability. Countries were then scored against these 13 rankings, and the number of times a country appeared in the top quintile of countries in a particular ranking was used as an indicator of its overall vulnerability.

Progress continues to be made in the methodologies of deriving vulnerability metrics. For example, Rygel et al. (2006) have demonstrated the value of using a Pareto method for combining scores from a collection of indices without having to apply either implicit or explicit weightings. Alcamo et al. (2008) sought to increase the consistency of incorporating expert opinion on different disciplinary approaches (sociology, environmental psychology, economics, and political science) to the estimate of vulnerability, in this case of drought events, in three regions. Based on inference models about what contributes to vulnerability to drought and using fuzzy set theory (Eierdanz et al., 2008) to compute susceptibilities, they were able to show that high combined susceptibilities were associated with water stress crises.

Perch-Nielsen (2010) developed an index to estimate the vulnerability of beach tourism using a systematic approach by establishing a framework to identify the types of indicators needed and a systematic approach to identify indicators that covered the range of countries and time scales. The derivation of the index from the separate indicators was also subjected to robustness (sensitivity) testing to determine the most appropriate methods of scaling and combining the measures.

14.5.4. Assessment of Existing and Proposed Metrics for Adaptation

Srinivasan and Prabhakar (2009) conducted a wide-ranging stakeholder survey to assess the attitudes to, and requirements for, indicators of adaptation. Stakeholders agreed that no single metric can capture the multiple dimensions of adaptation and that refinements of methodologies (e.g., rationale for index selection, aggregation methods, and data checking) are badly needed. Preston et al. (2009) have suggested that, rather than seeking particular metrics, researchers should focus on developing rigorous processes for selecting metrics that can be applied in a range of contexts. But metrics for adaptation remain a necessity. Their derivation challenges the adaptation community to clarify its goals, conceptual models, definitions, and applications. But both theory and practice have shown indices alone are not sufficient to guide decisions on which adaptation actions to take, on how to modify sustainable development activities, or on resource allocation. Downing (2003) noted that the climate change community was far from adopting common standards, paradigms, or analytic language. This still appears to be true, making the search for commonly accepted metrics, even within well-specified contexts, a challenging task.

14.6. Addressing Maladaptation

The adaptation literature is replete with advice to avoid maladaptation, but it is less clear precisely what is included as "maladaptation." In a general sense maladaptation refers to actions, or inaction that may lead to increased risk of adverse climate-related outcomes, increased vulnerability to climate change, or diminished welfare, now or in the future (see Glossary). For example, the construction of well-engineered climate-resilient roads designed to withstand current and future climate extremes may foster new settlement into areas highly exposed to the impacts of future climates; or increased water harvesting upstream to cope with erratic rainfall may harm and reduce the opportunities for communities downstream to manage their own risks. Actions that are potentially maladaptive need not be inadvertent (as in the IPCC AR3 and AR4 definition), nor be "taken ostensibly to avoid or reduce vulnerability to climate change" (Barnett and O'Neill, 2010) as the actions may be assessed as appropriate in the context of the full range of climate and non-climate considerations and pressures that apply to the decision. There should be clarity as to what is maladaptive action, or lack of action, lest the avoidance of potential maladaptation becomes a barrier to effective implementation of adaptation. In the road example above, the immediate and multiple benefits to the community of a reliable road system (including as evacuation route in floods, etc.) might be judged as outweighing the longer term risk of inappropriate settlement patterns (Lamhauge et al., 2011). This may be seen as an example of an "unavoidable" *ex post* maladaptation (see Section 16.3.6.1) as it is an appropriate decision based on the information and circumstances at the time. The true maladaptation in this case would be the failure to implement appropriate incentives or regulations to avoid vulnerable settlements in the highly exposed areas.

The wide range of actions and circumstances that have been described as maladaptive demonstrates the complexity of the concept and terminology. Thomsen et al. (2012) describe actions that are not respectful of the intrinsic integrity and internal self-regulation of social-ecological systems as manipulative and likely to prove maladaptive. Their example is the management of Noosa Beach in northern Australia, where the coastline is characterized by cycles of erosion and depletion of beach sands. Rather than enhance the self-regulatory processes and adapting by managed retreat and expansion according to the cycle, management has sought to maintain a static beach profile through hard constructions and beach nourishment. Niemeyer et al. (2005) also describe the state of individual beliefs about climate change that might change from adaptive to inaction and possibly maladaptive behaviors as the perceived magnitude of climate change increases, while Eriksen et al. (2011) and Brown (2011) discuss avoiding outcomes that are

[7] CRED, the Centre for Research on the Epidemiology of Disasters, has maintained a database of disasters, including those that are climate related. Rationale, methodologies, and data are available at http://www.cred.be/.

essentially maladaptive as they run counter to sustainable development goals.

14.6.1. Causes of Maladaptation

Maladaptation arises in many forms but several broad causes can be identified. Actions that may benefit a particular group, or sector, at a particular time may prove to be maladaptive to those same groups or sectors in future climates or to other groups or sectors in existing climates. For example, some development policies and measures that deliver short-term benefits or economic gains but lead to greater vulnerability in the medium to long term, such as in cases where the construction of "hard" infrastructure reduces the flexibility and the range of future adaptation options (Adger et al., 2003b; Eriksen and Kelly, 2007; OECD, 2009), or the failure to encompass the full range of risks in the design of new structures, such as the effects of increasing storm surge in the design of a coastal defense system (UNFCCC, 2007). Adaptation efforts aimed at armoring the coastline may result in coastal erosion elsewhere while building levees along a flood-prone area provides protection to coastal population and infrastructure but might encourage unwanted development within that area, often accentuated by an exaggerated sense of safety (Grothmann and Patt, 2005; Repetto, 2008; National Research Council, 2011) and the levees may increase damage when they fail, as in Bangladesh in 1999 and New Orleans in 2003 (Huq and Khan, 2006; Masozera et al., 2007; Pouliotte et al., 2009). Similarly, agricultural policies that promote the growing of high-yielding crop varieties through subsidies with the objective of boosting production and increasing revenues may achieve these objectives in the short term, but will also reduce agro-biodiversity and increase exposure and vulnerability of mono-crops to climate change and finally undermine the adaptive capacity of farmers in the long term (World Bank, 2010).

Another cause of maladaptation is the failure to account for multiple interactions and feedbacks between systems and sectors leading to inadequate or inaccurate information for developing adaptive responses and strategies that are maladaptive (Scheraga et al., 2003; Satterthwaite et al., 2009; Pittock, 2011). An assessment of the downstream impacts of upstream rainwater harvesting in a semiarid basin in southern India showed that, once the full range of externalities were accounted for, the net benefits were insufficient to pay back investment costs (Bouma et al., 2011). Similarly, the conversion of coastal mangroves into shrimp farms may lead to increased economic productivity and improved livelihoods, but could also lead to increased vulnerability to flooding and storm surges (Klein, 2010). Maladaptation may also occur if the true potential of an option or a technology is unduly over-emphasized, making it over-rated. Floating gardening has been suggested as an example in this connection (Irfanullah, 2009, 2013). Further examples of the range of maladaptive actions across a range of sectors and regions in this report are outlined in Table 14-4.

14.6.2. Screening for Maladaptation

Five dimensions of maladaptation were identified by Barnett and O'Neill (2010), including actions that, relative to alternatives: (1) increase emissions of GHGs, (2) disproportionately burden the most vulnerable, (3) have high opportunity costs, (4) reduce incentives and capacity to adapt, and (5) set paths that limit future choices. These dimensions are useful pointers to the potential for maladaptation but their application depends on subjective assessments. The first suggests that any action that increases GHG emissions is maladaptive, whereas a judgment on the relative benefits and dis-benefits will need to be made in such cases; the second turns on the interpretation of "disproportionately;" and the third on "high" and on how opportunity costs are compared with current benefits. The dimensions were used by Barnett and O'Neill (2010) to describe maladaptive potential of the Wonthaggi desalinization plant to improve water supply to Melbourne, Australia. The plant was included as part of a wider water management plan for Melbourne that includes both demand- and supply-side management and incentives (Heffernan, 2012; Porter, 2013). Barnett and O'Neill (2010) argue that the plant (1) will increase GHG emissions (even if the planned wind power

Table 14-4 | A selection of examples of actual or potential maladaptive actions from this report.

Broad type of maladaptive action	Examples in AR5
Failure to anticipate future climates. Large engineering projects that are inadequate for future climates. Intensive use of non-renewable resources (e.g., groundwater) to solve immediate adaptation problem	22.3, 22.4.8.5
Engineered defenses that preclude alternative approaches such as EBA	Box CC-EA; 15.2.2
Adaptation actions not taking wider impacts into account	22.4.5.8, 25.4.2, and 26.9.4
Awaiting more information, or not doing so, and eventually acting either too early or too late. Awaiting better "projections" rather than using scenario planning and adaptive management approaches	7.5.1.2.2, 8.5.2, and 16.5.2
Forgoing longer term benefits in favor of immediate adaptive actions; depletion of natural capital leading to greater vulnerability	13.2.1.3; 22.4.5.8; 25.9.1
Locking into a path dependence, making path correction difficult and often too late	16.3.2; FAQ 25.1
Unavoidable ex post maladaptation, e.g., expanding irrigation that eventually will have to be replaced in the distant future	17.5; see also 5 and 6 above
Moral hazard, i.e., encouraging inappropriate risk taking based, e.g., on insurance, social security net, or aid backup	17.5 and 29.8
Adopting actions that ignore local relationships, traditions, traditional knowledge, or property rights, leading to eventual failure	12.3, 12.5.2; 26.9.4
Adopting actions that favor directly or indirectly one group over others leading to breakdown and possibly conflict	13.1.1 and 13.1.4
Retaining traditional responses that are no longer appropriate	21.3.2 and 22.4.5.8
Migration may be adaptive or maladaptive or both depending on context and the individuals involved	26.2.1, 26.8.3, 29.3.3, 29.6.2.4

Note: These examples of maladaptation represent a set of cases found in the report that might help the readers to understand the rich range of circumstances in which maladaptive actions might arise. They do not represent a formal categorization of type of maladaptation.

energy source is completed); (2) may lead to higher water costs that will disproportionally affect the poorer households; (3) may divert money and attention from more cost-effective recycling and rainwater harvesting; (4) may reduce incentives to adapt through water conservation approaches; and (5) as a large sunk cost has locked out other options. The plant also affected significant cultural sites of the Bunurong Aboriginal community (Lee and Chung, 2007).

14.6.3. Experiences with Maladaptation

Maladaptation is a cause of increasing concern to adaptation planners, where intervention in one sector could increase vulnerability of another sector or increase the vulnerability of a group to future climate change. An example is the situation experienced by subsistence and smallholder agriculturalists in Palca, Bolivia, who in the face of stressors relating to land access, small holdings, and so forth moved away from their long established practices of diversification of crop varieties and planting locations to more intensive farming practices and cash cropping. They are now seeing evidence of climate change, and the new practices make them more vulnerable to these changes, leading to a risk of insufficient adaptation and maladaptation (McDowell and Hess, 2012). But there can also be tensions between development goals and climate change goals, where people may be aware of a climate related risk but are willing to take that risk (or they may have limited choice) given their current circumstances (IPCC, 2012, Section 4.2.2).

Some studies warn against the simplistic use of maladaptation to communicate the state of high exposure to risks resulting from certain type of livelihoods. For example, the periodic movement of the nomadic pastoralists following the grass and water is a traditional and effective way of dealing with climate variability (Agrawal and Perrin, 2008), but is increasingly being described by some as maladaptive. More focused studies such as Young et al. (2009) put the breakdown of traditional pastoralism in the Sudan into the wider social and political context that led to restrictions on movement, asset stripping, and escalating violence and was undermined by policies not conducive to mobility.

14.7. Research and Data Gaps

A long list of research questions could be identified and prioritized to address gaps and assist the practice of adaptation, and many of these are found in the subsequent adaptation chapters. In this chapter research priorities would range from metrics for adaptation to the psychology of communication about livelihood and life-threatening events. But, the preparation of this report has shown that the practice of adaptation has outstripped the rate at which relevant peer-reviewed research can be produced and disseminated.

Many dedicated researches have become engaged in smaller, often community-based or urban activities where results can be gathered in relatively short time frames and direct interactions between the researchers and the implementers are common. Here research and action can, and are, serving each other and these interactions can be encouraged with support for further cross-community, cross-cultural, and cross-sectoral comparisons.

Effective and timely interaction is more difficult at larger scales. National or multinational programs are often longer and complex and it is difficult to identify the "adaptation" effort within a wider set of policy objectives. Research inputs into decision making too often centers only on better projections of future conditions or *post hoc* assessments of completed projects. The task is made more difficult by relatively short-term research grants, often starting late in the process, or after the process is finished, and by the often rapid turnover of planning and implementation staff, making a close working relationship difficult. But there are models that work. Models based on established and ongoing research teams with a close link to policy such as the EC programs and its formation of targeted research teams across the European Union, CSIR in South Africa, Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the National Climate Change Research Facility (NCCARF) in Australia, the Corps of Engineers and the Regional Integrated Sciences and Assessments (RISAs) in the USA, and UKCIP and its successors in the UK do appear to be more effective in maintaining a dialog with those "on the ground," and this shows in the number of well designed, insightful, and reviewed documents arising from these collaborations.

Unfortunately this model has not been replicated at scale in most developing countries. One might ask why is there only one reference in this volume to any lesson learned from the PPCR – a billion dollar program set up to better understand the challenges of integrating, or mainstreaming, adaptation into development planning with on the ground implementation of many larger than normal adaptation activities? The planning for the PPCR started only in 2008, but the planning process itself is of research relevance, and over the past 2 to 3 years 18 countries have been working through how to bring adaptation into their national planning programs; it is surely a core research interest and opportunity and one whose lifespan already exceeds that of many research projects. Similarly the Adaptation Fund is mentioned only descriptively in these chapters. So where were the groups of independent researchers observing from their point of view, comparing and contrasting countries, and simply conducting the process of independent and collaborative research? The benefit would flow not just from the research itself but also from the interactions with those charged with implementing adaptation and from the challenge to interpret that research so that its implications are relevant to the users, be they government officials or smallholder farmers.

There are models in developing countries. The Consultative Group on International Agricultural Research (CGIAR) network is already making contributions, albeit in the broad domain of agriculture which may be another model. The Coordinated Regional Climate Downscaling Experiment (CORDEX) project will make high-quality high-resolution climate projections available to all countries. The NEPAD Framework for African Agricultural Productivity is another, and there are numerous smaller and effective research efforts too numerous to list here, but few can claim even regional coverage. The Cancun Agreement has already raised the prospect of establishing in a developing country "an international centre to enhance adaptation research and coordination." This may provide the vehicle to tackle some of the problems described above. The UN Agencies, the MDBs, and many bilateral agencies, which are heavy users and sometimes producers of "research," could be major beneficiaries and supporters.

Two points in a review of a decade of experience in the RISA process in the USA stand out. One was an insistence that research team members should primarily be residents in their region of study, and to paraphrase another insight, "knowing what one ought to do is not the same as knowing how to do it" (Pulwarty et al., 2009). In arguing for the establishment of the skills to establish an Australian film industry, Phillip Adams advised the Prime Minister,[8] "It's time to see our own landscapes, hear our own voices and dream our own dreams." Those words could just as well apply to tackling adaptation.

References

Aakre, S. and D.T.G. Rübbelke, 2010: Objectives of public economic policy and the adaptation to climate change. *Journal of Environmental Planning and Management*, **53**, 767-791.

Adaptation Fund Board, 2013: *Operational Policies and Guidelines for Parties to Access Resources from the Adaptation Fund*. The Adaptation Fund, Washington, DC, USA, 52 pp.

Adger, W.N., 2001: Scales of governance and environmental justice for adaptation and mitigation of climate change. *Journal of International Development*, **13(7)**, 921-931.

Adger, W.N., 2003: Social capital, collective action, and adaptation to climate change. *Economic Geography*, **79**, 387-404.

Adger, W.N., 2006: Vulnerability. *Global Environmental Change*, **16**, 268-281.

Adger, W.N. and J. Barnett, 2009: Four reasons for concern about adaptation to climate change. *Environment and Planning A*, **41(12)**, 2800-2805.

Adger, W.N. and P.M. Kelly, 1999: Social vulnerability to climate change and the architecture of entitlements. *Mitigation and Adaptation Strategies for Global Change*, **4**, 253-266.

Adger, W.N., N. Brooks, G. Bentham, M. Agnew, and S. Eriksen, 2003a: *New Indicators of Vulnerability and Adaptive Capacity*. Technical Report No. 7, Tyndall Centre for Climate Research, School of Environmental Sciences, University of East Anglia, Norwich, UK, 128 pp.

Adger, W.N., S. Huq, K. Brown, D. Conway, and M. Hulme, 2003b: Adaptation to climate change in the developing world. *Progress in Development Studies*, **3(3)**, 179-195.

Adger, W.N., N.W. Arnell, and E.L. Tompkins, 2005: Successful adaptation to climate change across scales. *Global Environmental Change*, **15(2)**, 77-86.

Adger, W.N., S. Agrawala, M. Mirza, C. Conde, K. O'Brien, J. Pulhin, R. Pulwarty, B. Smit, and K. Takahashi, 2007: Assessment of adaptation practices, options, constraints and capacity. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 717-743.

Adger, W.N., S. Dessai, M. Goulden, M. Hulme, I. Lorenzoni, D. Nelson, L.-O. Naess, J. Wolf, and A. Wreford, 2009a: Are there social limits to adaptation to climate change? *Climatic Change*, **93(3-4)**, 335-354.

Adger, W.N., I. Lorenzoni, and K. O'Brien (eds.), 2009b: *Adapting to Climate Change: Thresholds, Values, Governance*. Cambridge University Press, Cambridge, UK and New York, NY, USA, 514 pp.

Adler, C.E., D. McEvoy, P. Chhetri, and E. Kruk, 2013: The role of tourism in a changing climate for conservation and development. A problem-oriented study in the Kailash Sacred Landscape, Nepal. *Policy Sciences*, **46**, 160-178.

Agrawal, A., 2010: Local institutions and adaptation to climate change. In: *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World* [Mearns, R. and A. Norton (eds.)]. World Bank Publications, Washington, DC, USA, pp. 173-197.

Agrawal, A. and N. Perrin, 2008: *Climate Adaptation, Local Institutions, and Rural Livelihood*. IFRI Working Paper W08I-6, International Forestry Resources and Institutions Program (IFRI), School of Natural Resources and Environment, University of Michigan, Ann Arbor, MI, USA, 17 pp.

Agrawala, S., 2005: Putting climate change in the development mainstream: introduction and framework. In: *Bridge Over Troubled Waters: Linking Climate Change and Development* [Agrawala, S. (ed.)]. Organization for Economic Co-operation and Development (OECD), OECD Publishing, Paris, France, pp. 23-43.

Agrawala, S. and M. Carraro, 2010: *Assessing the Role of Microfinance in Fostering Adaptation to Climate Change*. ENV/WKP(2010)1, OECD Environment Working Paper No. 15, Organization for Economic Co-operation and Development (OECD), OECD Publishing, Paris, France, 37 pp.

Agrawala, S. and M. van Aalst, 2008: Adapting development cooperation to adapt to climate change. *Climate Policy*, **8(2)**, 183-193.

Agrawala, S., M. Carraro, N. Kingsmill, E. Lanzi, M. Mullan, and G. Prudent-Richard, 2011: *Private Sector Engagement in Adaptation to Climate Change: Approaches to Managing Climate Risks*. OECD Environment Working Paper No. 39, Organization for Economic Co-operation and Development (OECD), OECD Publishing, Paris, France, 55 pp.

Alam, K., M. Shamsuddoha, T. Tanner, M. Sultana, M.J. Huq, and S.S. Kabir, 2011: The political economy of climate resilient development planning in Bangladesh. *IDS Bulletin*, **42(3)**, 52-61.

Alderman, H., H. Hoogeveen, and M. Rossi, 2009: Preschool nutrition and subsequent schooling attainment: longitudinal evidence from Tanzania. *Economic Development and Cultural Change*, **57**, 239-260.

Alcamo, J., L. Acosta-Michlik, A. Carius, D. Krömker, F. Eierdanz, R. Klein, D., Kromker, and D. Tänzler, 2008: A new approach to quantifying and comparing vulnerability to drought. *Regional Environmental Change*, **8**, 137-149.

Alexander, C., N. Bynum, E. Johnson, U. King, T. Mustonen, P. Neofotis, N. Oettle, C. Rosenzweig, C. Sakakibara, V. Shadrin, M. Vicarelli, J. Waterhouse, and B. Weeks, 2011: Linking indigenous and scientific knowledge of climate change. *BioScience*, **61(6)**, 477-484.

Alexander, N., 2010: *The Country Policy and Institutional Assessment (CPIA) and Allocation of IDA Resources: Suggestions for Improvements to Benefit African Countries*. Economic Governance Program, Heinrich Bell Foundation, Washington, DC, USA, 43 pp.

Allison, E.H., A.L. Perry, M.-C. Badjeck, W.N. Adger, K. Brown, D. Conway, A.S. Halls, G.M. Pilling, J.D. Reynolds, N.L. Andrew, and N.K. Dulvy, 2009: Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries*, **10**, 173-196.

Anguelovski, I. and J. Carmin, 2011: Climate action planning in Quito, Ecuador. In: *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, C., W.D. Solecki, S.A. Hammer, and S. Mehotra (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 262 pp.

Anon, 2009: *Building Coast Smart Communities: How Will Maryland Adapt to Climate Change?* Consensus Building Institute and MIT-USGS Science Impact Collaborative, Cambridge, MA, USA and the Maryland Department of Natural Resources, Annapolis, MD, USA, 21 pp.

Arnell, N.W., 2009: Adapting to climate change: an evolving research programme. *Climatic Change*, **100(1)**, 107-111.

Arnold, G., H. Bos, R. Doef, R. Goud, N. Kielen, and F. van Lujin, 2011: *Water Management in the Netherlands*. This report is a joint publication of the Ministry of Infrastructure and Environment, Directorate-General Water and Rijkswaterstaat, Centre for Water Management, The Hague, Netherlands, 80 pp.

Atteridge, A., 2011: *Will Private Finance Support Climate Change Adaptation in Developing Countries? Historical Investment Patterns as a Window on Future Private Climate Finance*. SEI Working Paper No. 2011-5, Stockholm Environment Institute (SEI), Stockholm, Sweden, 35 pp.

Ayers, J., 2011: Resolving the adaptation paradox: exploring the potential for deliberative adaptation policy-making in Bangladesh. *Global Environmental Politics*, **11(1)**, 62-88.

Ayers, J. and D. Dodman, 2010: Climate change adaptation and development I: the state of the debate. *Progress in Development Studies*, **10(2)**, 161-168.

Bambrick, H.J., A.G. Capon, G.B. Barnett, R.M. Beaty, and A.J. Burton, 2011: Climate change and health in the urban environment: adaptation opportunities in Australian cities. *Asia Pacific Journal of Public Health*, **23(2)**, 67-79.

Banerjee, S., J.-Y. Gerlitz, and D. Kniveton, 2013: A methodology for assessing patterns of labour migration in mountain communities exposed to water hazards. In: *Disentangling Migration and Climate Change: Methodologies, Political*

[8] http://www.abc.net.au/dimensions/dimensions_in_time/Transcripts/s796788.htm, accessed 3rd Oct 2013.

Discourses and Human Rights [Faist, T. and J. Schade (eds.)]. Springer International, Heidelberg, Germany and New York, NY, USA, pp. 81-100.

Bannayan, M. and G. Hoogenboom, 2008: Weather analogue: a tool for real-time prediction of weather data realizations based on a modified *k*-nearest neighbor approach. *Environmental Modeling and Software*, **23(6)**, 703-713.

Barnett, J. and S. O'Neill, 2010: Maladaptation. *Global Environmental Change*, **20(2)**, 211-213.

Barron, S., G. Canete, J. Carmichael, D. Flanders, E. Pond, S. Sheppard, and K. Tatebe, 2012: A climate change adaptation planning process for low-lying, communities vulnerable to sea level rise. *Sustainability*, **4(12)**, 2176-2208.

Bartlett, S., D. Dodman, J. Hardoy, D. Satterthwaite, and C. Tacoli, 2009: *Social Aspects of Climate Change in Urban Areas in Low- and Middle-Income Nations.* Paper presented at the World Bank Fifth Urban Research Symposium, "Cities and Climate Change: Responding to an Urgent Agenda," 28-30 June 2009, Marseilles, France, Research Cluster 5, 44 pp.

Berkes, F., 2007: Understanding uncertainty and reducing vulnerability: lessons from resilience thinking. *Natural Hazards*, **41(2)**, 283-295.

Berkhout, F., 2005: Rationales for adaptation in EU climate change policies. *Climate Policy*, **5(3)**, 377-391.

Berkhout, F., J. Hertin, and D.M. Gann, 2006: Learning to adaptation: organizational adaptation to climate change impacts. *Climatic Change*, **78(1)**, 135-156.

Bhutta, Z.A., T. Ahmed, R.E. Black, S. Cousens, K. Dewey, E. Giugliani, B.A. Haider, B. Kirkwood, S.S. Morris, H.P.S. Sachdev, and M. Shekar, 2008: What works? Interventions for maternal and child undernutrition and survival. *Lancet*, **371(9610)**, 417-440.

Biderman, C., M. Smolka, and A. Sant'Anna, 2008: *Urban Housing Informality: Does Building and Land Use Regulation Matter?* Lincoln Institute of Land Policy, *Land Lines*, July 2008, Cambridge, MA, USA, 6 pp.

Birkmann, J. and K. von Teichman, 2010: Integrating disaster risk reduction and climate change adaptation: key challenges – scales, knowledge, and norms. *Sustainability Science*, **5(2)**, 171-184.

Blanco, H., M. Alberti, A. Forsyth, K.J. Krizek, D.A. Rodríguez, E. Talen, and C. Ellis, 2009: Hot, congested, crowded and diverse: emerging research agendas in planning. *Progress in Planning*, **71(4)**, 153-205.

Bolte, A., C. Ammer, M. Löf, P. Madsen, G. Nabuurs, P. Schall, P. Spathelf, and J. Rock, 2009: Adaptive forest management in central Europe: climate change impacts, strategies and integrative concept. *Scandinavian Journal of Forest Research*, **24(6)**, 473-482.

Bosello, F., C. Carraro, and E. De Cian, 2009: *An Analysis of Adaptation as a Response to Climate Change*. Report prepared for the Copenhagen Consensus 2009, Copenhagen Consensus Center, Copenhagen Business School, Frederiksberg, Denmark, 76 pp.

Bouma, J.A., W. Trent, and M. Laurens, 2011: The downstream externalities of harvesting rainwater in semi-arid watersheds: an Indian case study. *Agricultural Water Management*, **98(7)**, 1162-1170.

Boyd, E. and H. Osbahr, 2010: Responses to climate change: exploring organisational learning across internationally networked organisations for development. *Environmental Education Research*, **16(5-6)**, 629-643.

Brooks, N. and W.N. Adger, 2003: *Country Level Risk Measures of Climate-related Natural Disasters and Implications for Adaptation to Climate Change.* Tyndall Centre for Climate Research Working Paper No. 26, University of East Anglia, Norwich, UK, 25 pp.

Brooks, N., W.N. Adger, and P.M. Kelly, 2005: The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Global Environmental Change Part A*, **15(2)**, 151-163.

Brooks, N., S. Anderson, J. Ayers, I. Burton, and I. Tellam, 2011: *Tracking Adaptation and Measuring Development*. IIED Working Paper No. 1, Climate Change Group, International Institute for Environment and Development (IIED), London, UK, 35 pp.

Brown, A., M. Gawith, K. Lonsdale, and P. Pringle, 2011: *Managing Adaptation: Linking Theory and Practice*. UK Climate Impacts Programme (UKCIP), School of Geography and the Environment, Oxford University Centre for the Environment (OUCE), Oxford, UK, 47 pp.

Brown, C., Y. Ghile, M. Laverty, and K. Li, 2012: Decision scaling: linking bottom-up vulnerability analysis with climate projections in the water sector. *Water Resources Research*, **48(9)**, W09537, doi:10.1029/2011WR011212.

Brown, K., 2011: Sustainable adaptation: an oxymoron? *Climate and Development*, **3(1)**, 21-31.

Bryan, E., T.T. Deressa, G.A. Gbetibouo, and C. Ringler, 2009: Adaptation to climate change in Ethiopia and South Africa: options and constraints. *Environmental Science and Policy*, **12(4)**, 413-426.

Bulkeley, H. and M. Betsill, 2005: Rethinking sustainable cities: multilevel governance and the 'urban' politics of climate change. *Environmental Politics* **14**, 42-63.

Burton, I., 1996: The growth of adaptation capacity: practice and policy. In: *Adapting to Climate Change: An International Perspective* [Smith, J., N. Bhatti, G. Menzhulin, R. Benioff, M.I. Budyko, M. Campos, B. Jallow, and F. Rijsberman (eds.)]. Springer-Verlag, Berlin Heidelberg, Germany, pp. 55-67.

Burton, I., 2004: *Climate Change and the Adaptation Deficit*. Occasional Paper 1, The Adaptation and Impacts Research Group (AIRG), Meteorological Service of Canada, Environment Canada, Toronto, ON, Canada, 6 pp.

Burton, I. and E. May, 2004: The adaptation deficit in water resources management. *IDS Bulletin*, **35(3)**, 31-37.

Burton, I., S. Huq, B. Lim, O. Pilifosova, and E.L. Schipper, 2002: From impacts assessment to adaptation priorities: the shaping of adaptation policy. *Climate Policy*, **2(2)**, 145-159.

Burton, I., E. Diringer, and J. Smith, 2006: *Adaptation to Climate Change: International Policy Options*. The Pew Center on Global Climate Change, Arlington, VA, USA, 28 pp.

Cardona, O.D., 2005. *Indicators of Disaster Risk and Risk Management: Program for Latin America and the Caribbean Summary Report*. Environment Division, Sustainable Development Department, Inter-American Development Bank, Washington, DC, USA, 43 pp.

Carmin, J. and D. Dodman, 2013: Engaging science and managing scientific uncertainty in urban climate adaptation planning. In: *Successful Adaptation to Climate Change: Linking Science and Policy in a Rapidly Changing World* [Moser, S.C. and M.T. Boykoff (eds.)]. Routledge, Abingdon UK and New York, NY, USA, pp. 220-234.

Carmin, J., I. Anguelovski, and D. Roberts, 2012: Urban climate adaptation in the global south: planning in an emerging policy domain. *Journal of Planning Education and Research*, **32(1)**, 18-32.

Carpenter, S.R., H.A. Mooney, J. Agard, D. Capistrano, R.S. DeFries, S. Diaz, T. Dietz, A.K. Duraiappah, A. Oteng-Yeboah, H.M. Pereira, C. Perrings, W.V. Reid, J. Sarukhan, R.J. Scholes, and A. Whyte, 2009: Science for managing ecosystem services: beyond the millennium ecosystem assessment. *Proceedings of the National Academy of Sciences of the United States of America*, **106(5)**, 1305-1312.

Carter, T.R., M.L. Parry, H. Harawasa, and S. Nishioka, 1994: *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations*. CGER-I015-'94, Climate Change Impacts and Adaptations, Intergovernmental Panel on Climate Change, World Meteorological Organization (WMO)/United Nations Environment Programme (UNEP), Published by the Department of Geography, University College London, London, UK and the Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Japan, 59 pp.

CCCCC, 2011: *Developing an Implementation Plan for the CARICOM "Regional Framework for Achieving Development Resilient to Climate Change"*. Feedback report from in-country dialogues, produced by Climate Risk Management, Ltd., (Acclimatise), for the Caribbean Community Climate Change Centre (CCCCC), Acclimatise, Newark, UK, 138 pp.

CGIAR, 2012: *Gender and Climate Change Research in Agriculture and Food Security for Development*. Training Guide, The CGIAR Program on Climate Change, Agriculture and Food Security (CCAFS), Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 127 pp.

Chinowsky, P., C. Hayles, A. Schweikert, N. Strzepek, K. Strzepek, and C.A. Schlosser, 2011: Climate change: comparative impact on developing and developed countries. *Engineering Project Organization Journal*, **1(1)**, 67-80.

Christensen, K., S. Raihan, R. Ahsan, A.M.N. Uddin, C.S. Ahmed, and H. Wright, 2012: *Ensuring Access for the Climate Vulnerable in Bangladesh: Financing Local Adaptation*. ActionAid Bangladesh (AAB), Action Research for Community Adaptation in Bangladesh (ARCAB), Bangladesh Centre for Advanced Studies (BCAS), and International Centre for Climate Change and Development (ICCCAD), AAB, Dhaka, Bangladesh, 126 pp.

Chuku, C.A., 2009: Pursuing an integrated development and climate policy framework in Africa: options for mainstreaming. *Mitigation and Adaptation Strategies for Global Change*, **15(1)**, 41-52.

Ciplet, D., S. Fields, K. Madden, M. Khan, and J.T. Roberts, 2012: *The Eight Unmet Promises of Fast Start Climate Finance*. IIED Briefing, International Institute for Environment and Development (IIED), London, UK, 8 pp.

Ciscar, J.-C., A. Iglesias, L. Feyen, L. Szabó, D. Van Regemorter, B. Amelung, R. Nicholls, P. Watkiss, O.B. Christensen, and R. Dankers, 2011: Physical and economic consequences of climate change in Europe. *Proceedings of the National Academy of Sciences of the United States of America*, **108**, 2678-2683.

Climate Investment Funds, 2009: *The Selection of Countries to Participate in the Pilot Program for Climate Resilience (PPCR)*. Report of the Expert Group (established by the Pilot Programme on Climate Resilience Subcommittee, PPCR-SC), to the PPCR Subcommittee, Climate Investment Funds, The World Bank Group, Washington, DC, USA, 61 pp.

Cline, W.R., 2007: *Global Warming and Agriculture: Impact Estimates by Country*. The Center for Global Development (CGD) and the Peterson Institute for International Economics, Washington, DC, USA, 186 pp.

Coles, A.R. and C.A. Scott, 2009: Vulnerability and adaptation to climate change and variability in semi-arid rural southeastern Arizona, USA. *Natural Resources Forum*, **33(4)**, 297-309.

Collins, K. and R. Ison, 2009: Jumping off Arnstein's ladder: social learning as a new policy paradigm for climate change adaptation. *Environmental Policy and Governance*, **19(6)**, 358-373.

Colombo, A.F. and P.H. Byer, 2012: Adaptation, flexibility and project decision-making with climate change uncertainties. *Impact Assessment and Project Appraisal*, **30(4)**, 229-241.

Compston, H., 2010: The politics of climate policy: strategic options for national governments. *Political Quarterly*, **81(1)**, 107-115.

Conway, D. and L. Schipper, 2011: Adaptation to climate change in Africa: challenges and opportunities identified from Ethiopia. *Global Environmental Change*, **21(1)**, 227-237.

Conway, G., 2009: *The Science of Climate Change in Africa: Impacts and Adaptation*. Grantham Institute for Climate Change Discussion Paper No. 1, Imperial College, London, UK, 24 pp.

Convention on Biological Diversity, 2009: *Connecting Biodiversity and Climate Change Mitigation and Adaptation: Report of the Second Ad Hoc Technical Expert Group on Biodiversity and Climate Change*. CBD Technical Series No. 41, Secretariat of the CBD, Montreal, QC, Canada, 126 pp.

Corfee-Morlot, J., I. Cochran, S. Hallegatte, and P.-J. Teasdale, 2011: Multilevel risk governance and urban adaptation policy. *Climatic Change*, **104(1)**, 169-197.

Costello, A., M. Abbas, A. Allen, S. Ball, S. Bell, R. Bellamy, S. Friel, N. Groce, A. Johnson, M. Kett, M. Lee, C. Levy, M. Maslin, D. McCoy, B. McGuire, H. Montgomery, D. Napier, C. Pagel, J. Patel, J.A. Puppim de Oliveira, N. Redclift, H. Rees, D. Rogger, J. Scott, J. Stephenson, J. Twigg, J. Wolff, and C. Patterson, 2009: Managing the health effects of climate change. *Lancet*, **373**, 1693-1733.

Costello, A., M. Maslin, H. Montgomery, A.M. Johnson, and P. Ekins, 2011: Global health and climate change: moving from denial and catastrophic fatalism to positive action. *Philosophical Transactions of the Royal Society A*, **369(1942)**, 1866-1882.

Crawford, S.E.S. and E. Ostrom, 1995: A grammar of institutions. *American Political Science Review*, **89**, 582-600.

Cutter, S.L., C.T. Emrich, J.J. Web, and D. Morath, 2009: *Social Vulnerability to Climate Variability Hazards: A Review of the Literature*. Final Report to Oxfam America, Hazards Vulnerability Research Institute, University South Carolina, Columbia, SC, USA, 44 pp.

Dawson, R., 2007: Re-engineering cities: a framework for adaptation to global change. *Philosophical Transactions of the Royal Society A*, **365(1861)**, 3085-3098.

Day, J.W., D.F. Boesch, E.J. Clairain, G.P. Kemp, S.B. Laska, W.J. Mitsch, K. Orth, H. Mashriqui, D.J. Reed, L. Shabman, C.A. Simenstad, B.J. Streever, R.R. Twilley, C.C. Watson, J.T. Wells, and D.F. Whigham, 2007: Restoration of the Mississippi Delta: lessons from Hurricanes Katrina and Rita. *Science*, **315(5819)**, 1679-1684.

De Bruin, K., R.B. Dellink, A. Ruijs, L. Boldwidt, A. van Buuren, J. Graveland, R.S. de Groot, P.J. Kuikman, S. Reinhard, R.P. Roetter, V.C. Tassone, A. Verhagen, and E.C. van Ierland, 2009: Adapting to climate change in the Netherlands: an inventory of climate adaptation options and ranking of alternatives. *Climatic Change*, **95(1-2)**, 23-45.

DEFRA, 2012: *UK Climate Change Risk Assessment: Government Report*. Presented to Parliament pursuant to Section 56 of the Climate Change Act 2008, Department for Environment, Food and Rural Affairs (DEFRA), The Stationery Office (TSO), Norwich, UK, 43 pp.

Deressa, T., R. Hassan, and C. Ringler, 2009b: *Assessing Household Vulnerability to Climate Change: The Case of Farmers in the Nile Basin of Ethiopia.* IFPRI Discussion Paper 00935, International Food Policy Research Institute (IFPRI), Washington, DC, USA, 18 pp.

Deressa, T.T., R.M. Hassan, C. Ringler, T. Alemu, and M. Yesuf, 2009a: Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia. *Global Environmental Change*, **19(2)**, 248-255.

Dessai, S. and M. Hulme, 2004: Does climate adaptation policy need probabilities? *Climate Policy*, **4(2)**, 107-128.

Dessai, S., X. Lu, and J.S. Risbey, 2005: On the role of climate scenarios for adaptation planning. *Global Environmental Change*, **15(2)**, 87-97.

Dilley, M., R.S. Chen, U. Deichmann, A.L. Lerner-Lam, and M. Arnold, with J. Agwe, P. Buys, O. Kjekstad, B. Lyon, and G. Yetman, 2005: *Natural Disaster Hotspots: A Global Risk Analysis*. Disaster Risk Management Series No. 5, The International Bank for Reconstruction and Development / The World Bank and Columbia University, World Bank, Washington, DC, USA, 132 pp.

Dolan, A.H. and I.J. Walker, 2003: Understanding vulnerability of coastal communities to climate change related risks. *Journal of Coastal Research*, **39(SI)**, 1317-1324.

Doria, M.D., E. Boyd, E.L. Tompkins, and W.N. Adger, 2009: Using expert elicitation to define successful adaptation to climate change. *Environmental Science and Policy*, **12(7)**, 810-819.

Dovers, S.R. and A.A. Hezri, 2010: Institutions and policy processes: the means to the ends of adaptation. *Climate Change*, **1(2)**, 212-231.

Dow, K., F. Berkhout, B.L. Preston, R.J.T. Klein, G. Midgley, and M.R. Shaw, 2013: Limits to adaptation. *Nature Climate Change*, **3**, 305-307.

Dowlatabadi, H., 2007: On integration of policies for climate change global change. *Mitigation and Adaptation Strategies for Global Change*, **12**, 651-663.

Downing, T., 2003: Toward a vulnerability/adaptation science: lessons from famine early warning and food security. In: *Climate Change Adaptive Capacity and Development* [Smith, J., R. Klein, and S. Huq (eds.)]. Imperial College Press, London, UK, pp. 77-100.

Downing, T.E., M.J. Watts, and H.G. Bohle, 1995: Climate change and food insecurity: towards a sociology and geography of vulnerability. In: *Climate Change and World Food Security* [Downing, T.E. (ed.)]. Springer, Berlin, Germany, pp. 183-206.

Dudley, N., S. Stolton, A. Belokurov, L. Krueger, N. Lopoukhine, K. MacKinnon, T. Sandwith, and N. Sekhran (eds.), 2010: *Natural Solutions: Protected Areas Helping People Cope with Climate Change*. The International Union for Conservation of Nature-World Commission on Protected Areas (IUCN-WCPA), the Nature Conservancy (TNC), the United Nations Development Programme (UNDP), the Wildlife Conservation Society (WCS), The World Bank, and the World Wildlife Fund (WWF), IUCN-WCPA and WWF International, Gland, Switzerland, TNC, Arlington, VA, USA, UNDP, New York, NY, USA, WCS, Bronx, NY, USA, and The World Bank, Washington, DC, USA, 126 pp.

Eakin, H. and M.C. Lemos, 2006: Adaptation and the state: Latin America and the challenge of capacity-building under globalization. *Global Environmental Change*, **16(1)**, 7-18.

Eakin, H. and A. Luers, 2006: Assessing the vulnerability of social-environmental systems. *Annual Review of Environment and Resources*, **31(1)**, 365-394.

Eakin, H., E.L. Tompkins, D.R. Nelson, and J.M. Anderies, 2012: Hidden costs and disparate uncertainties: trade-offs in approaches to climate policy. In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, W.N., I. Lorenzoni, and K.L. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 212-226.

Ebi, K., 2011: Climate change and health risks: assessing and responding to them through "adaptive management". *Health Affairs*, **30(5)**, 924-930.

Ebi, K.L. and I. Burton, 2008: Identifying practical adaptation options: an approach to address climate change-related health risks. *Environmental Science and Policy*, **11(4)**, 359-369.

ECA, 2009: *Shaping Climate-Resilient Development: A Framework for Decision-Making.* A Report of the Economics of Climate Adaptation (ECA) Working Group, a partnership of the Climate Works Foundation, Global Environment Facility, European Commission, McKinsey and Company, The Rockefeller Foundation, Standard Chartered Bank, and Swiss Re, 159 pp.

Edwards, F., J. Dixon, S. Friel, G. Hall, K. Larsen, S. Lockie, B. Wood, M. Lawrence, I. Hanigan, A. Hogan, and L. Hattersley, 2011: Climate change adaptation at the intersection of food and health. *Asia Pacific Journal of Public Health*, **23(2)**, 91-104.

Eierdanz, F., J. Alcamo, L. Acosta-Milchlik, D. Krömker, and D. Tänzler, 2008: Using fuzzy set theory to address the uncertainty of susceptibility of drought. *Regional Environmental Change*, **8(4)**, 197-205.

Engle, N.L. and M.C. Lemos, 2010: Unpacking governance: building adaptive capacity to climate change of river basins in Brazil. *Global Environmental Change*, **20(1)**, 4-13.

Eriksen, S.H. and P.M. Kelly, 2007: Developing credible vulnerability indicators for climate adaptation policy assessment. *Mitigation and Adaptation Strategies for Global Change*, **12**, 495-524.

Eriksen, S., P. Aldunce, C.S. Bahinipati, R. D'Almeida Martins, J.I. Molefe, C. Nhemachena, K. O'Brien , F. Olorunfemi, J. Park, L. Sygna, and K. Ulsrud, 2011: When not every response to climate change is a good one: identifying principles for sustainable adaptation. *Climate and Development*, **3(1)**, 7-20.

European Commission, 2009: *Adapting to Climate Change: Towards a European Framework for Action*. White Paper, Brussels 1.4.2009 COM(2009) 147 final, Publications Office of the European Union, Luxembourg, Luxembourg, 16 pp.

Fankhauser, S. and I. Burton, 2011: Spending adaptation money wisely. *Climate Policy*, **11(3)**, 1037-1049.

FAO, 2007: *Adaptation to Climate Change in Agriculture, Forestry and Fisheries: Perspective, Framework and Priorities.* Interdepartmental Working Group on Climate Change, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 24 pp.

FEMA, 2010: *Hazard Mitigation Assistance Unified Guidance*. Federal Emergency Management Agency (FEMA), Department of Homeland Security, FEMA, Washington, DC, USA, 168 pp.

Ferrara de Giner, G., M.T. Martelo, R. Lairet, A. Villamizar, and J.C. Sánchez, 2012: A proposal for community adaptive capacity on adaptation to climate change: San Pedro community, Caracas, Venezuela. In: *E-Annals from ABES-AIDIS. XXXIII Congreso Interamericano de Engenharia Sanitária e Ambiental (Associação Brasileira de Engenharia Sanitária e Ambiental*), Theme VIII-024, pp. 1-7.

Finzi Hart, J.A., P.M. Grifman, S.C. Moser, A. Abeles, M.R. Myers, S.C. Schlosser, and J.A. Ekstrom, 2012: *Rising to the Challenge: Results of the 2011 Coastal California Adaptation Needs Assessment*. Technical Report: USCSG-TR-01-2012, University of Southern California (USC) Sea Grant, USC, Los Angeles, CA, 76 pp.

Ford, J.D., L. Berrang-Ford, and J. Paterson, 2011: A systematic review of observed climate change adaptation in developed nations. *Climatic Change*, **106(2)**, 327-336.

Fünfgeld, H. and D. McEvoy, 2011: *Framing Climate Change Adaptation in Policy and Practice*. VCCCAR Working Paper 1, VCCCAR Project: Framing Adaptation in the Victorian Context, Victorian Centre for Climate Change Adaptation Research (VCCCAR), Melbourne, Australia, 65 pp.

Furlow, J., J.B. Smith, G. Anderson, W. Breed, and J. Padgham, 2011: Building resilience to climate change through development assistance: USAID's Climate Adaptation Program. *Climatic Change*, **108(3)**, 411-421.

Füssel, H.-M., 2007: Vulnerability: a generally applicable conceptual framework for climate change research. *Global Environmental Change*, **17(2)**, 155-167.

Füssel, H.-M., 2009: An updated assessment of the risks from climate change based on research published since the IPCC Fourth Assessment Report. *Climatic Change*, **97(3-4)**, 469-482.

Füssel, H.-M., 2010: How inequitable is the global distribution of responsibility, capability, and vulnerability to climate change: a comprehensive indicator-based assessment. *Global Environmental Change*, **20(4)**, 597-611.

Füssel, H.-M. and R.J.T. Klein, 2006: Climate change vulnerability assessments: an evolution of conceptual thinking. *Climatic Change*, **75(3)**, 301-329.

Gagnon-Lebrun, F. and S. Agrawala, 2006: *Progress on Adaptation to Climate Change in Developed Countries: An Analysis of Broad Trends.* Organisation for Economic Co-operation and Development (OECD), OECD Publishing, Paris, France, 61 pp.

Gardiner, D., M. Anderson, R. Schlesinger, J. Fox Gorte, and D. Zeller, 2007: *Climate Risk Disclosure by the S&P 500*. David Gardiner & Associates report for Ceres and Calvert analyzing the S&P 500 CDP4 responses to the Carbon Disclosure Project information request regarding the risks and opportunities of climate change, Ceres, Boston, MA, USA, 72 pp., www.calvert.com/documents/ceres_calvert_sandp_500.pdf.

Garg, A., R.C. Dhiman, S. Bhattacharya, and P.R. Shukla, 2009: Development, malaria and adaptation to climate change: a case study from India. *Environmental Management*, **43(5)**, 779-789.

GEF, 2002: *Note on GEF Support for National Adaptation Plans of Action (NAPA)*. GEF/C.19/Inf.7, May 8, 2002, Global Environment Facility (GEF), GEF Secretariat, Washington, DC, USA, 28 pp.

Gething, P.W., D.L. Smith, A.P. Patil, A.J. Tatem, R.W. Snow, and S.I. Hay, 2010: Climate change and the global malaria recession. *Nature*, **465(7296)**, 342-345.

Ghimire, Y.N., G.P. Shivakoti, and S.R. Perret, 2010: Household-level vulnerability to drought in hill agriculture of Nepal: implications for adaptation planning. *International Journal of Sustainable Development and World Ecology*, **17(3)**, 225-230.

GIZ, 2011: *Making Adaptation Count: Concepts and Options for Monitoring and Evaluation of Climate Change Adaptation*. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, on behalf of Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (BMZ), and The World Resources Institute (WRI), GIZ, Eschborn, Germany, 92 pp.

Glatzel, K., H. Wright, and Z. Makuch, 2012: Technology innovation and the law - the example of climate adaptation technologies. In: *Environmental and Energy Law* [Makuch, K.E. and R. Pereira (eds.)]. Wiley-Blackwell, Chichester, UK, pp. 92-116.

Goldman, R.L., H. Tallis, P. Kareiva, and G.C. Daily, 2008: Field evidence that ecosystem service projects support biodiversity and diversify options. *Proceedings of the National Academy of Sciences of the United States of America*, **105(27)**, 9445-9448.

Goldstein, J.H., G. Caldarone, T.K. Duarte, D. Ennaanay, N. Hannahs, G. Mendoza, S. Polasky, S. Wolny, and G.C. Daily, 2012: Integrating ecosystem-service tradeoffs into land-use decisions. *Proceedings of the National Academy of Sciences of the United States of America*, **109(19)**, 7565-7570.

Gonzalez, P., R.P. Neilson, J.M. Lenihan, and R.J. Drapek, 2010: Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change. *Global Ecology and Biogeography*, **19(6)**, 755-768.

Government of Nepal, 2011: *National Framework on Local Adaptation Plan for Action (LAPA)*, Kathmandu, Nepal, 56 pp.

Green Climate Fund, 2013a: *Governing Instrument for the Green Climate Fund*, Green Climate Fund, Interim Secretariat of the Green Climate Fund, Bonn, Germany, 16 pp., gcfund.net/fileadmin/00_customer/documents/pdf/GCF-governing_instrument-120521-block-LY.pdf.

Green Climate Fund, 2013b: *Business Model Framework: Objectives*, *Results and Performance Indicators*. GCF/B.04/03, Green Climate Fund, Meeting of the Board, 26-28 June 2013, Songdo, Republic of Korea, 27 pp., www.gcfund.net/fileadmin/00_customer/documents/pdf/B-04_03_BMF_Objectives_Results_PerformanceIndicators_10Jun13.pdf.

Grothmann, T. and A. Patt, 2005: Adaptive capacity and human cognition: the process of individual adaptation to climate change. *Global Environmental Change*, **15(3)**, 199-213.

GTZ, 2008: *Adaptation and Refinement of the World Bank's "Country Policy and Institutional Assessment" (CPIA)*. Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, on behalf of Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (BMZ), and the Global Public Policy Institute (GPPi), GTZ, Eschborn, Germany, 90 pp.

Guariguata, M., 2009: El manejo forestal en el contexto de la adaptación al cambio climático. *Revista de Estudios Sociales*, **32**, 98-112.

Gupta, J., C. Termeer, J. Klostermann, S. Meijerink, M. van den Brink, P. Jong, S. Nooteboom, and E. Bergsma, 2010: The adaptive capacity wheel: a method to assess the inherent characteristics of institutions to enable the adaptive capacity of society. *Environmental Science and Policy*, **13(6)**, 459-471.

Haines, A., R.S. Kovats, D. Campbell-Lendrum, and C. Corvalan, 2006: Climate change and human health: impacts, vulnerability, and mitigation. *Lancet*, **367(9528)**, 2101-2109.

Hallegatte, S., 2009: Strategies to adapt to an uncertain climate change. *Global Environmental Change*, **19(2)**, 240-247.

Hallegatte, S., 2011: How economic growth and rational decisions can make disaster losses grow faster than wealth. Policy Research Working Paper 5617, Office of the Chief Economist, Sustainable Development Network, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, 21 pp.

Hamin, E.M. and N. Gurran, 2009: Urban form and climate change: balancing adaptation and mitigation in the U.S. and Australia. *Habitat International*, **33(3)**, 238-245.

Hardoy, J. and P. Romero Lankao, 2011: Latin American cities and climate change: challenges and options to mitigation and adaptation responses. *Current Opinion in Environmental Sustainability*, **3(3)**, 158-163.

Harlan, S.L. and D.M. Ruddel, 2011: Climate change and health in cities: impacts of heat and air pollution and potential co-benefits from mitigation and adaptation. *Current Opinion in Environmental Sustainability*, **3(3)**, 126-134.

Harsdorff, M., M. Lieuw-Kie-Song, and M. Tsukamoto, 2011: *Towards an ILO Approach to Climate Change Adaptation*. ILO Employment Working Paper No. 104, International Labour Organization (ILO), Geneva, Switzerland, 85 pp.

Heffernan, O., 2012: No going back. *Nature*, **491**, 659-661.

Heltberg, R., P.B. Siegel, and S.L. Jorgensen, 2009: Addressing human vulnerability to climate change: toward a "no-regrets" approach. *Global Environmental Change*, **19(1)**, 89-99.

Hinkel, J., 2011: Indicators of vulnerability and adaptive capacity: towards a clarification of the science-policy interface. *Global Environmental Change*, **21(1)**, 198-208.

Hochrainer, S., R. Mechler, and G. Pflug, 2007: Climate change and weather insurance in Malawi: assessing the impact. In: *Feasibility of Risk Financing Schemes for Climate Adaptation: The Case of Malawi* [Suarez, P., J. Linnerooth-Bayer, and R. Mechler (eds.)]. International Institute for Applied Systems Analysis (IIASA) Report to the World Bank Development Economics Research Group, IIASA, Laxenburg, Austria, pp. 53-86.

Hoddinott, J., J.A. Maluccio, J.R. Behrman, R. Flores, and R. Martorell, 2008: Effect of a nutrition intervention during early childhood on economic productivity in Guatemalan adults. *Lancet*, **371(9610)**, 411-416.

Hoegh-Guldberg, O., 2011: Coral reef ecosystems and anthropogenic climate change. *Regional Environmental Change*, **11(Suppl. 1)**, 215-227.

Hoeppe, P. and E.N. Gurenko, 2006: Scientific and economic rationales for innovative climate insurance solutions. *Climate Policy*, **6(6)**, 607-620.

Huang, C., P. Vaneckova, X. Wang, G. Fitzgerald, Y. Gro, and S. Tong, 2011: Constraints and barriers to public health adaptation to climate change: a review of the literature. *American Journal of Preventive Medicine*, **40(2)**, 183-190.

Hulme, M., 2009: *Why We Disagree about Climate Change: Understanding Controversy, Inaction and Opportunity*. Cambridge University Press, Cambridge, UK and New York, NY, USA, 392 pp.

Huntjens, P., C. Pahl-Wostl, and J. Grin, 2010: Climate change adaptation in European river basins. *Regional Environmental Change*, **10(4)**, 263-284.

Huq, S. and M.R. Khan, 2006: Equity in National Adaptation Programs of Action (NAPAs): the case of Bangladesh. In: *Fairness in Adaptation to Climate Change* [Adger, W.N., J. Paavola, S. Huq, and M.J. Mace (eds.)]. MIT Press, Cambridge, MA, USA, pp. 131-153.

Huq, S., S. Kovats, H. Reid, and D. Satterthwaite, 2007: Editorial: reducing risks to cities from disasters and climate change. *Environment and Urbanization*, **19(1)**, 3-15.

Hussey, K. and S. Dovers, 2006: Trajectories in Australian water policy. *Journal of Contemporary Water Research and Education*, **135(1)**, 36-60.

IEG, 2009: *The World Bank's Country Policy and Institutional Assessment: An Evaluation*. Independent Evaluation Group (IEG), The World Bank Group, Washington, DC, USA, 142 pp.

IFC, 2010: *Climate Risk and Financial Institutions: Challenges and Opportunities*. International Finance Corporation (IFC), Washington, DC, USA, 120 pp.

IPCC, 2001: *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. *Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [McCarthy, J.J., O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1032 pp.

IPCC, 2007a: *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K. and A. Reisinger (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

IPCC, 2007b: *Climate Change 2007: Impacts, Adaptation and Vulnerability*. *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 976 pp.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp.

Irfanullah, H.M., 2009: Floating gardening in Bangladesh: already affected by climate variability? In: *Biodiversity Conservation and Response to Climate Variability at Community Level* [Irfanulla, H.M., R. Amin, and A. Nishat (eds.)]. International Union for Conservation of Nature (IUCN), United Nations Environment Programme (UNEP), and United Nations University (UNU), IUCN, Dhaka, Bangladesh, pp. 7-14.

Irfanullah, H.M., 2013. Floating gardening: a local lad becoming a climate celebrity? *Clean Slate*, **88**, 26-27.

Irfanullah, H.M., A. Adrika, A. Ghani, Z.A. Khan, and M.A. Rashid, 2011a: Introduction of floating gardening in the north-eastern wetlands of Bangladesh for nutritional security and sustainable livelihoods. *Renewable Agriculture and Flood Systems*, **23(2)**, 89-96.

Irfranullah, H.M., M.A.K. Azad, A.K.M. Kamruzzaman, and M.A. Wahed, 2011b: Floating gardening in Bangladesh: a means to rebuild lives after devastating flood. *Indian Journal of Traditional Knowledge*, **10(1)**, 31-38.

Jentsch, A. and C. Beierkuhnlein, 2008: Research frontiers in climate change: effects of extreme meteorological events on ecosystems. *Comptes Rendus Geoscience*, **340(9-10)**, 621-628.

Jones, H.P., D.G. Hole, and E.S. Zavaleta, 2012: Harnessing nature to help people adapt to climate change. *Nature Climate Change*, **2**, 504-509.

Kalame, F.B., D. Kudejira, and J. Nkem, 2011: Assessing the process and options for implementing National Adaptation Programmes of Action (NAPA): a case study from Burkina Faso. *Mitigation and Adaptation Strategies for Global Change*, **16(5)**, 535-553.

Kasperson, J.X. and R.E. Kasperson, 2001: *Global Environmental Risk*. United National University Press, Tokyo, Japan and New York, NY, USA, 574 pp.

Kates, R.W. and T.J. Wilbanks, 2003: Making the global local: responding to climate change concerns from the ground. *Environment*, **45(3)**, 12-23.

Kates, R.W., W.R. Travis, and T.J. Wilbanks, 2012: Transformational adaptation when incremental adaptation climate change insufficient. *Proceedings National Academy Sciences of the United States of America*, **109(19)**, 7156-7161.

Kaufman, R. and F.W. English, 1979: *Needs Assessment: Concept and Application*. Educational Technology Publications, Englewood Cliffs, NJ, USA, 355 pp.

Khan, M.M.R., S.H. Miah, and H.M. Irfanullah, 2013: Small-scale silage-making technology for the extreme poor on floodplains. *International Journal of Environmental Studies*, **70(2)**, 192-202.

Khattri, A., D. Parameshwar, and S. Pellech, 2010: *Opportunities for Private Sector Engagement in Urban Climate Change Resilience Building*. Report by Intellectual Capital Advisory Services Pvt. Ltd. (Intellecap) with the support of the Asian Cities Climate Change Resilience Network (ACCCRN) and the Rockefeller Foundation, Intellecap, Hyderabad, India and the Rockefeller Foundation, Bangkok, Thailand, 90 pp.

Kiparsky, M., A. Milman, and S. Vicuña, 2012: Climate and water: knowledge of impacts to action on adaptation. *Annual Review of Environment and Resources*, **37(1)**, 163-194.

Klein, R.J.T., 2010: Mainstreaming climate adaptation in development: a policy dilemma. In: *Climate Governance and Development* [Ansohn, A. and B. Pleskovic (eds.)]. Berlin Workshop Series 2010, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, pp. 35-52.

Klein, R.J.T. and A. Möhner, 2011: The political dimension of vulnerability: implications for the Green Climate Fund. *IDS Bulletin*, **42(3)**, 15-22.

Klein, R.J.T., R.J. Nicholls, and F. Thomalla, 2003: Resilience to natural hazards: how useful is this concept? *Global Environmental Change Part B: Environmental Hazards*, **5(1-2)**, 35-45.

Klein, R.J.T., S. Huq, F. Denton, T.E. Downing, R.G. Richels, J.B. Robinson, and F.L. Toth, 2007: Inter-relationships between adaptation and mitigation. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contributions of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikot, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 745-777.

Koetse, M.J. and P. Rietveld, 2012: Adaptation to climate change in the transport sector. *Transport Reviews*, **32(3)**, 267-286.

Kovats, S. and R. Akhtar, 2008: Climate, climate change and human health in Asian cities. *Environment and Urbanization*, **20(1)**, 165-175.

KPMG International, 2008: *Climate Changes Your Business: KPMG's Review of the Business Risks and Economic Impacts at Sector Level*. KPMG International, Amstelveen, Netherlands, 76 pp.

Krasny, M.E., C. Lundholm, and R. Plummer, 2010: Resilience in social-ecological systems: the roles of learning and education. *Environmental Education Research*, **16(5-6)**, 463-474.

Kumamoto, M. and A. Mills, 2012: What African countries perceive to be adaptation priorities: results from 20 countries in the Africa Adaptation Programme. *Climate and Development*, **4(4)**, 265-274.

Lamhauge, N., E. Lanzi, and S. Agrawala, 2011: *Monitoring and Evaluation for Adaptation: Lessons from Development Co-operation Agencies*. OECD Environment Working Paper No. 38, Organization for Economic Co-operation and Development (OECD) Publishing, Paris, France, 49 pp.

Laukkonen, J., P.K. Blanco, J. Lenhart, M. Keiner, B. Cavric, and C. Kinuthia-Njenga, 2009: Combining climate change adaptation and mitigation measures at the local level. *Habitat International*, **33(3)**, 287-292.

LDC Expert Group, 2009: *The Least Developed Countries National Adaptation Programmes of Action: Overview of Preparation, Design of Implementation Strategies and Submission of Revised Project Lists and Profiles*. United Nations Framework Convention on Climate Change (UNFCCC), UNFCCC Secretariat, Bonn, Germany, 32 pp.

LDC Expert Group, 2012: *National Adaptation Plans: Technical Guidelines for the National Adaptation Plan Process.* LDC Expert Group, United Nations Framework Convention on Climate Change (UNFCCC), UNFCCC Secretariat, Bonn, Germany, 148 pp.

Learmonth, G., D.E. Smith, W.H. Sherman, M.A. White, and J. Plank, 2011: A practical approach to the complex problem of environmental sustainability: the UVa Bay Game. *The Innovation Journal*, **16(1)**, 2-8.

Lee, K.S. and E.S. Chung, 2007: Hydrological effects of climate change, groundwater withdrawal, and land use in a small Korean watershed. *Hydrological Processes*, **21(22)**, 3046-3056.

Lempert, R.J. and M.E. Schlesinger, 2000: Robust strategies for abating climate change. *Climatic Change*, **45(3-4)**, 387-401.

Levina, E., 2007: *Adaptation to Climate Change: International Agreements for Local Needs*. COM/ENV/EPOC/IEA/SLT(2007)6, Organization for Economic Co-Operation and Development (OECD) and the International Energy Agency (IEA), OECD and IEA, Paris, France, 60 pp.

Lonergan, S., K. Gustavson, and M. Harrower, 1999: Mapping human insecurity. In: *Environmental Change, Adaptation, and Security* [Lonergen, S.C. (ed.)]. NATO/Kluwer, Dordrecht, Netherlands, pp. 397-413.

MacLean, D., 2008: *ICTs, Adaptation to Climate Change, and Sustainable Development at the Edges*. IISD Commentary, International Institute for Sustainable Development (IISD), Winnipeg, MB, Canada, 5 pp.

Mallawaarachchi, T. and A. Foster, 2009: *Dealing with Irrigation Drought: The Role of Water Trading in Adapting to Water Shortages in 2007-08 in the Southern Murray-Darling Basin*. ABARE Research Report 09.6 to the Department of the Environment, Water, Heritage, and the Arts, Australian Bureau of Agriculture and Resource Economics (ABARE), Canberra, Australia, 32 pp.

Martens, P., D. McEvoy, and C. Chang, 2009: The climate change challenge: linking vulnerability, adaptation, and mitigation. *Current Opinion in Environmental Sustainability*. **1(1)**, 14-18.

Masozera, M., M. Bailey, and C. Kerchner, 2007: Distribution of impacts of natural disasters across income groups: a case study of New Orleans. *Ecological Economics* **63(2-3)**, 299-306

Mawdsley, J.R., R. O'Malley, and D.S. Ojima, 2009: A review of climate-change adaptation strategies for wildlife management and biodiversity conservation. *Conservation Biology*, **23(5)**, 1080-1089.

McDowell, J.Z. and J.J. Hess, 2012: Accessing adaptation: multiple stressors on livelihoods in the Bolivian Highlands under a changing climate. *Global Environmental Change*, **22(2)**, 342-352.

McEvoy, D., S. Lindley, and J. Handley, 2006: Adaptation and mitigation in urban areas: synergies and conflicts. *Proceedings of the Institution of Civil Engineers: Municipal Engineer*, **159(4)**, 185-191.

McGray, H., R. Bradley, A. Hammill, E.L. Schipper, and J. Parry, 2007: *Weathering the Storm: Options for Framing Adaptation and Development*. World Resources Institute, Washington, DC, USA, 57 pp.

McKenzie Hedger, M., R. Connell, and P. Bramwell, 2006: Bridging the gap: empowering adaptation decision-making through the UK Climate Impacts Programme. *Climate Policy*, **6,** 201-215.

McKenzie Hedger, M., T. Mitchell, J. Leavy, M. Greenly, A. Downie, and L. Horrocks, 2008: *Desk Review: Evaluation of Adaptation to Climate Change from a Development Perspective*. Report commissioned by the GEF Evaluation Office (EO) and financed by DFID, as part of the GEF Evaluation Office International Conference on Evaluating Climate Change and Development (Alexandria, May 10th to 13th, 2008), Institute of Development Studies (IDS), London, UK, 60 pp.

McKillip, J., 1987: *Need Analysis: Tools for the Human Services and Education*. Sage Publications, Thousand Oaks, CA, USA, 143 pp.

McMichael, A.J. and E. Lindgren, 2011: Climate change: present and future risks to health, and necessary responses. *Journal of Internal Medicine*, **270(5)**, 401-413.

Mechler, R., S. Hochrainer, G. Pflug, A. Lotsch, and K. Williges, 2010: *Assessing the Financial Vulnerability to Climate-Related Natural Hazards*. World Bank Policy Research Paper No. 5232, Background Paper to the 2010 World Development Report, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 30 pp.

Mertz, O., K. Halsnaes, J.E. Olsen, and K. Rasmussen, 2009: Adaptation to climate change in developing countries. *Environmental Management*, **43(5)**, 743-752.

Meze-Hausken, E., A. Patt, and S. Fritz, 2009: Reducing climate risk for micro-insurance providers in Africa: a case study of Ethiopia. *Global Environmental Change*, **19(1)**, 66-73.

Moench, M., E. Fajber, A. Dixit, E. Caspari, and A. Pokhrel, 2009: *Catalyzing Climate and Disaster Resilience. Processes for Identifying Tangible and Economically Robust Strategies*. Final Report of the Risk to Resilience Study, Institute for Social and Environmental Transition (ISET), ISET-Nepal, Kathmandu, Nepal, 324 pp.

Moody, P. and C. Brown, 2012: Modeling stakeholder-defined climate risk on the Upper Great Lakes. *Water Resources Research*, **48(10)**, doi:10.1029/2012WR012497.

Mooney, H., A. Larigauderie, M. Cesario, T. Elmquist, O. Hoegh-Guldberg, S. Lavorel, G. Mace, M. Palmer, R. Scholes, and T. Yahara, 2009: Biodiversity, climate change, and ecosystem services. *Current Opinion in Environmental Sustainability*, **1**, 46-54.

Morecroft, M.D. and C. E. Cowan, 2010: Responding to climate change: an essential component of sustainable development in the 21st century. *Local Economy*, **25(3)**, 170-175.

Morris, J., 2007: Ecological engineering in intertidial saltmarshes. *Hydrobiologia*, **192**, 161-168.

Moser, S.C., 2006: *Asset-Based Approaches to Poverty Reduction in a Globalized Context: An Introduction to Asset Accumulation Policy and Summary of Workshop Findings*. Global Economy and Development Working Paper, Brookings Institution, Washington, DC, USA, 39 pp.

Moser, S.C., 2009: Governance and the art of overcoming barriers to adaptation. *Magazine of the International Human Dimensions Programme on Global Environmental Change*, **3**, 31-36.

Moser, S.C. and J.A. Ekstrom, 2011: Taking ownership of climate change: participatory adaptation planning in two local case studies from California. *Journal of Environmental Studies and Sciences*, **1(1)**, 63-74.

Moser, S.C. and D. Satterthwaite, 2010: Toward pro-poor adaptation to climate change in the urban centers of low- and middle-income countries. In: *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World* [Mearns, R. and A. Norton (eds.)]. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, pp. 231-258.

Moss, R.H., A.L. Brenkert, and E.L. Malone, 2001: *Vulnerability to Climate Change: A Quantitative Approach*. Technical Report PNNL-SA-33642, Prepared by the Pacific Northwest National Laboratory for the Department of Energy, Office of Scientific and Technical Information, Oak Ridge, TN, USA and U.S. Department of Commerce, Springfield, VA, USA, 70 pp.

Moss, R.H., E.L. Malone, N.L. Engle, A. de Bremond, and A. Delgado, 2012: *Ready or Not: Towards a Resilience Framework for Making Climate-Change Adaptation Decisions.* Report prepared for the World Bank by the Joint Global Change Research Institute.

National Research Council, 2011: *Adapting to the Impacts of Climate Change*. America's Climate Choices: Panel on Adapting to the Impacts of Climate Change, National Research Council, The National Academies Press, Washington, DC, USA, 292 pp.

NCCARF, 2012: *Climate Change Adaptation Research in Australia: An Overview of Research Funded by the National Climate Change Adaptation Research Facility*. National Climate Change Adaptation Research Facility (NCCARF), Griffith University Gold Coast, Queensland, Australia, 27 pp.

Nelson, D.R., W.N. Adger, and K. Brown, 2007: Adaptation to environmental change: contributions of a resilience framework. *Annual Review of Environment and Resources*, **32**, 395-419.

Nicholls, N., C.D. Butler, and I. Hanigan, 2006: Inter-annual rainfall variations and suicide in New South Wales, Australia, 1964-2001. *International Journal of Biometeorology*, **50(3)**, 139-143.

Niemeyer, S., J. Petts, and K. Hobson, 2005: Rapid climate change and society: assessing responses and thresholds. *Risk Analysis*, **25(6)**, 1443-1456.

O'Brien, K.L., 2012: Global environmental change II: from adaptation to deliberate transformation. *Progress in Human Geography*, **36(5)**, 667-676.

O'Brien, K.L., S. Eriksen, L.P. Nygaard, and A. Schjolden, 2007: Why different interpretations of vulnerability matter in climate change discourses. *Climate Policy*, **7(1)**, 73-88.

O'Neill, M.S. and K.L. Ebi, 2009: Temperature extremes and health: impacts of climate variability and change in the United States. *Journal of Occupational and Environmental Medicine*, **51(1)**, 13-25.

OECD, 2009: *Integrating Climate Change Adaptation into Development Co-operation: Policy Guidance*. Organization for Economic Co-operation and Development (OECD), OECD Publishing, Paris, France, 193 pp.

OECD, 2011: *Financing Climate Change Action and Boosting Technology Change: Key Messages and Recommendations from Current OECD Work*. Organisation for Economic Co-operation and Development (OECD), OECD Publishing, Paris, France, 15 pp.

Ogden, A.E. and J. L. Innes, 2009: Adapting to climate change in the southwest Yukon: locally identified research and monitoring needs to support decision making on sustainable forest management. *Arctic*, **62(2)**, 159-174.

Ormerod, S.J., M. Dobson, A.G. Hildrew, and C.R. Townsend, 2010: Multiple stressors in freshwater ecosystems. *Freshwater Biology*, **55(Suppl. 1)**, 1-4.

Osman-Elasha, B., N. Goutbi, E. Spanger-Siegfried, B. Dougherty, A. Hanafi, S. Zakieldeen, E-A. Sanjak, H.A. Atti, and H.M. Elhassan, 2009: Community development and coping with drought in rural Sudan. In: *Climate Change and Adaptation* [Leary, N., J. Adejuwon, V. Barros, I. Burton, J. Kulkarni, and R. Lasco (eds.)]. Earthscan, London, UK, pp. 90-108.

Paavola, J., 2008: Livelihoods, vulnerability and adaptation to climate change in Morogoro, Tanzania. *Environmental Science and Policy*, **11(7)**, 642-654.

Pant, L.P. and R. Heeks, 2011: *ICT-Enabled Development of Capacity for Climate Change Adaptation Centre for Development Informatics Institute for Development Policy and Management*. Centre for Development Informatics, Institute for Development Policy and Management, SED, University of Manchester, Manchester, UK, 26 pp.

Park, S.E., N.A. Marshall, E. Jakku, A.M. Dowd, S.M. Howden, E. Mendham, and A. Fleming, 2012: Informing adaptation responses to climate change through theories of transformation. *Global Environmental Change*, **22(1)**, 115-126.

Parry, M. and T. Carter, 1998: *Climate Impact and Adaptation Assessment: A Guide to the IPCC Approach*. Earthscan, London, UK, 166 pp.

Parry, M., N. Arnell, P. Berry, D. Dodman, S. Fankhauser, C. Hope, S. Kovats, R. Nicholls, D. Satterthwaite, R. Tiffin, and T. Wheeler, 2009: *Assessing the Costs of Adaptation to Climate Change: A Review of the UNFCCC and Other Recent Estimates*. International Institute for Environment and Development (IIED) and Grantham Institute for Climate Change, London, UK, 113 pp.

Patz, J.A., S.H. Olson, C.K. Uejio, and H.K. Gibbs, 2008: Disease emergence from global climate and land use change. *Medical Clinics of North America*, **92(6)**, 1473-1491.

Pelling, M., 2010: *Adaptation to Climate Change: From Resilience to Transformation*. Routledge, Abingdon, UK and New York, NY, USA, 224 pp.

Perch-Nielsen, S., 2010: The vulnerability of beach tourism to climate change - an index approach. *Climatic Change*, **100(3-4)**, 579-606.

Perkins, W., D., Ojima, and R., Corell, 2007: A survey of climate change adaptation planning. The Heinz Center, Washington, DC, USA, 52 pp.

Persson, A., R.J.T Klein, C.K. Siebert, A. Atteridge, B. Mueller, J. Hoffmaister, M. Lazarus, and T. Takama, 2009: *Adaptation Finance under a Copenhagen Agreed Outcome*. Stockholm Environment Institute (SEI), Stockholm, Sweden, 187 pp.

Peskett, L., N. Grist, M. Hedger, T. Lennartz-Walker, and I. Scholz, 2009: *Climate Change Challenges for EU Development Co-operation: Emerging Issues*. European Development Co-operation to 2020 Working Paper No. 3, European Association of Development Research and Training Institutes (EADI), Bonn, Germany, 23 pp.

Pittock, J., 2011: National climate change policies and sustainable water management: conflicts and synergies. *Ecology and Society*, **16(2)**, 25, www.ecologyandsociety.org/vol16/iss2/art25/.

Polsky, C., R. Neff, and B. Yarnal, 2007: Building comparable global change vulnerability assessments: the vulnerability scoping diagram. *Global Environmental Change*, **17(3-4)**, 472-485.

Porio, E., 2011: Vulnerability, adaptation, and resilience to floods and climate change-related risks among marginal, riverine communities in Metro Manila. *Asian Journal of Social Science*, **39(4)**, 425-445.

Porter, M.G., 2013: *A Tale of Two Cities: Desalination and Drought in Perth and Melbourne*. A report prepared for NCEDA under: 'Desalination for Australian Economic Development,' National Centre of Excellence in Desalination Australia (NCEDA), Alfred Deakin Research Institute, Deakin University, Melbourne, Australia, 43 pp.

Pouliotte, J., B. Smit, and L. Westerhoff, 2009: Adaptation and development: livelihoods and climate change in Subarnabad, Bangladesh. *Climate and Development*, **1(1)**, 31-46.

Prabhakar, S.V.R.K. and A. Srinivasan, 2011: Metrics for mainstreaming adaptation in agriculture sector. *Climate Change and Food Security in South Asia*, **8**, 551-567.

Pramova E., B. Locatelli, M. Brockhaus, and S. Fohlmeister, 2012: Ecosystem services in the National Adaptation Programmes of Action. *Climate Policy*, **12(4)**, 393-409.

Preston, B. and M. Stafford-Smith, 2009: *Framing Vulnerability and Adaptive Capacity Assessment: Discussion Paper*. CSIRO Climate Adaptation National Research Flagship Working Paper No. 2, CSIRO Marine and Atmospheric Research, Aspendale, Victoria, Australia, 52 pp.

Preston, B.L., R.M. Westaway, S. Dessai, and T. Smith, 2009: *Are We Adapting to Climate Change? Research and Methods for Evaluating Progress*. In: 89th American Meteorological Society Annual Meeting: Fourth Symposium on Policy and Socio-Economic Research, Phoenix, AZ, 15 pp.

Preston, B.L., R.M. Westaway, and E.J. Yuen, 2011a: Climate adaptation planning in practice: an evaluation of adaptation plans from three developed nations. *Mitigation and Adaptation Strategies for Global Change*, **16(4)**, 407-438.

Preston, B.L., E.J. Yuan, and R.M. Westaway, 2011b: Putting vulnerability to climate change on the map: a review of approaches, benefits and risks. *Sustainability Science*, **6**, 177-202.

Pulwarty, R.S., C. Simpson, and C.R. Nierenberg, 2009: The Regional Integrated Sciences and Assessments (RISA) Program: Crafting effective assessments for the long haul. In: *Integrated Regional Assessment of Global Climate Change* [Knight, C.G. and J. Jäger (eds.)]. Cambridge University Press, Cambridge, UK, pp. 367-393.

Ranger, N. and S.-L. Garbett-Shiels, 2012: Accounting for a changing and uncertain climate in planning and policymaking today: lessons for developing countries. *Climate and Development*, **4(4)**, 288-300.

Reid, H. and S. Huq, 2005: Climate change- biodiversity and livelihood impacts. In: *Tropical Forests and Adaptation to Climate Change: In Search of Synergies* [Robledo, C., M. Kanninen, and L. Pedroni (eds.)]. Center for International Forestry Research, Bogor Barat, Indonesia, pp. 57-70.

Repetto, R., 2008: *The Climate Crisis and the Adaptation Myth*. Yale School of Forestry and Environmental Studies Working Paper 13, Yale School of Forestry and Environmental Studies, New Haven, CT, USA, 21 pp.

Reser, J.P. and J.K. Swim, 2011: Adapting to and coping with the threat and impacts of climate change. *American Psychologist*, **66(4)**, 277-289.

Reser, J.P., G. Bradley, and M. Ellul, 2012: Coping with climate change: bringing psychological adaptation in from the cold. In: *Handbook of the Psychology of Coping: New Research* [Molinelli B. and V. Grimaldo (eds.)]. Nova Science Publishers, Hauppauge, NY, USA, pp. 1-34.

Revi, A., 2008: Climate change risk: an adaptation and mitigation agenda for Indian cities. *Environment and Urbanization*, **20(1)**, 207-229.

Reyer, C., M. Guericke, and P.L. Ibisch, 2009: Climate change mitigation via afforestation, reforestation and deforestation avoidance: and what about adaptation to environmental change? *New Forests*, **38(1)**, 15-34.

Ribot, J., 2010: Vulnerability does not fall from the sky: toward multiscale, pro-poor climate policy. In: *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World* [Mearns, R. and A. Norton (eds.)]. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, pp. 47-74.

Roberts, D., 2008: Thinking globally, acting locally – institutionalizing climate change at the local government level in Durban, South Africa. *Environment and Urbanization*, **20(2)**, 521-537.

Roberts, D., 2010: Prioritizing climate change adaptation and local level resilience in Durban, South Africa. *Environment and Urbanization*, **22(2)**, 397-413.

Rosenzweig, C., W. Solecki, S.A. Hammer, and S. Mehrotra, 2010: Cities lead the way in climate-change action. *Nature*, **467**, 909-911.

Rosenzweig, C., W.D. Solecki, R. Blake, M. Bowman, C. Faris, V. Gornitz, R. Horton, K. Jacob, A. LeBlanc, R. Leichenko, M. Linkin, D. Major, M. O'Grady, L. Patrick, E. Sussman, G. Yohe, and R. Zimmerman, 2011: Developing coastal adaptation to climate change in the New York City infrastructure-shed: process, approach, tools, and strategies. *Climatic Change*, **106(1)**, 93-127.

Rygel, L., D. O'Sullivan, and B. Yarnal, 2006: A method for constructing a social vulnerability index: an application to hurricane storm surges in a developed country. *Mitigation and Adaptation Strategies for Global Change*, **11**, 741-764.

Satterthwaite, D. and D. Dodman, 2009: The costs of adapting infrastructure to climate change. In: *Assessing the Costs of Adaptation to Climate Change: A Review of the UNFCCC and Other Recent Estimates* [Parry, M., N. Arnell, P. Berry, D. Dodman, S. Fankhauser, C. Hope, S. Kovats, R. Nicholls, D. Satterthwaite, R. Tiffin, and T. Wheeler (eds.)]. International Institute for Environment and

Development (IIED) and the Grantham Institute for Climate Change, IIED, London, UK, pp. 73-89.

Satterthwaite, D., S. Huq, H. Reid, M. Pelling, and P. Romero Lankao, 2009: Adapting to climate change in urban areas: the possibilities and constraints in low- and middle-income nations. In: *Adapting Cities to Climate Change* [Bicknell, J., D. Dodman, and D. Satterthwaite (eds.)]. Earthscan, London, UK, pp. 3-47.

Scheraga, J.D., K.L. Ebi, J. Furlow, and A.R. Moreno, 2003: From science to policy: developing responses to climate change. In: *Climate Change and Human Health: Risks and Responses* [McMichael, A.J., D. Lendrum, C.F. Corvalan, K.L. Ebi, A. Githeko, and J.D. Scheraga (eds.)]. World Health Organization (WHO), World Meteorological Organization (WMO), United Nations Environment Programme (UNDP), World Health Organization, Geneva, Switzerland, pp. 237-266.

Schipper, L., 2009: Meeting the crossroads? Exploring the linkages between climate change adaptation and disaster risk reduction. *Climate and Development*, **1(1)**, 16-30.

Schröter, D., C. Polsky, and A. Patt, 2005: Assessing vulnerabilities to the effects of global change: an eight step approach. *Mitigation and Adaptation Strategies for Global Change*, **10(4)**, 573-595.

Semenov, M.A., 2006: Using weather generators in crop modeling. *Acta Horticulturae*, **707**, 93-100.

Semenov, M.A., 2008: Simulation of extreme weather events by a stochastic weather generator. *Climate Research*, **35(3)**, 203-212.

Semenza, J.C., S. Herbst, A. Rechenburg, J.E. Suk, C. Hoser, C. Schreiber, and T. Kistemann, 2012: Climate change impact assessment of food- and waterborne diseases. *Critical Reviews in Environmental Science and Technology*, **42(8)**, 857-890.

Shikanga, O-T., D. Mutonga, M. Abade, S. Amwayi, M. Ope, H. Limo, E.D. Mintz, R.E. Quick, R.F. Breiman, and D.R. Feikin, 2009: High mortality in cholera outbreak in western Kenya after post-election violence in 2008. *The American Journal of Tropical Medicine and Hygiene*, **81(6)**, 1085-1090.

Sietz, D., M. Boschutz, and R.J.T. Klein, 2011a: Mainstreaming climate adaptation into development assistance: rationale, institutional barriers and opportunities in Mozambique. *Environmental Science and Policy*, **14(4)**, 493-502.

Sietz, D., M.K.B. Lüdeke, and C. Walther, 2011b: Categorisation of typical vulnerability patterns in global drylands. *Global Environmental Change*, **21(2)**, 431-440.

Skoufias, E. (ed.), 2012: *The Poverty and Welfare Impacts of Climate Change: Quantifying the Effects, Identifying the Adaptation Strategies*. World Bank Publications, Washington, DC, USA, 184 pp.

Smit, B. and O. Pilifosova, 2003: From adaptation to adaptive capacity and vulnerability reduction. In: *Climate Change, Adaptive Capacity and Development* [Smith, J.B., R.J.T. Klein, and S. Huq (eds.)]. Imperial College Press, London, UK, pp. 9-28.

Smit, B. and J. Wandel, 2006: Adaptation, adaptive capacity and vulnerability. *Global Environmental Change*, **16(3)**, 282-292.

Smit, B., O. Pilifosova, I. Burton, B. Challenger, S. Huq, R.J.T. Klein, and G. Yohe, 2001: Adaptation to climate change in the context of sustainable development and equity. In: *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [McCarthy, J.J., O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 877-912.

Smith, J.B., J.M. Vogel, and J.E. Cromwell III, 2009: An architecture for government action on adaptation to climate change. *Climatic Change*, **95 (1-2)**, 53-61.

Sovacool, B.K., 2011: Hard and soft paths for climate change adaptation. *Climate Policy*, **11(4)**, 1177-1183.

Sovacool, B.K., A.L. D'Agostino, H. Meenawat, and A. Rawlani, 2012: Expert views of climate change adaptation in least developed Asia. *Journal of Environmental Management*, **97**, 78-88.

Sowers, J., A. Vengosh, and E. Weinthal, 2011: Climate change, water resources, and the politics of adaptation in the Middle East and North Africa. *Climatic Change*, **104(3-4)**, 599-627.

Srinivasan, A. and S.V.R.K. Prabhakar, 2009: *Measures of Adaptation to Climatic Change and Variability (Adaptation Metrics)*. Final Report to the World Bank, Contract No. 7145543, Institute for Global Environmental Strategies (IGES) Research Report, IGES, Hayama, Japan and The World Bank, Washington, DC, USA, 108 pp., http://pub.iges.or.jp/modules/envirolib/view.php?docid=2940.

Stafford Smith, M., L. Horrocks, A. Harvey, and C. Hamilton, 2010: Rethinking adaptation for a 4°C world. *Philosophical Transactions of the Royal Society A*, **369(1934)**, 196-216.

Stern, N., 2006: *The Economics of Climate Change*. Cambridge University Press, Cambridge, UK, 712 pp.

Stokes, C. and M. Howden, 2010: *Adapting Agriculture to Climate Change: Preparing Australian Agriculture, Forestry and Fisheries for the Future*. CSIRO Publishing, Canberra, Australia, 296 pp.

Suarez, P., F. Ching, G. Ziervogel, I. Lemaire, D. Turnquest, J. Mendler de Suarez, and B. Wisner, 2009: Video-mediated approaches for community-level climate adaptation. *IDS Bulletin*, **39(4)**, 96-104.

Swart, R. and F. Raes, 2007: Making integration of adaptation and mitigation work mainstreaming into sustainable development policies? *Climate Policy*, **7**, 288-303.

Tengö, M. and K. Belfrage, 2004: Local management practices for dealing with change and uncertainty: a cross-scale comparison of cases in Sweden and Tanzania. *Ecology and Society*, **9(3)**, 4, www.ecologyandsociety.org/vol9/iss3/art4/.

The Climate Institute, 2011: *A Climate of Suffering: The Real Cost of Living with Inaction on Climate Change*. The Climate Institute, Melbourne and Sydney, Australia, 28 pp.

Thomsen, D.C., T.F. Smith, and N. Keys, 2012: Adaptation or manipulation? Unpacking climate change response strategies. *Ecology and Society*, **17(3)**, 20, www.ecologyandsociety.org/vol17/iss3/art20/.

Tol, R.S.J., T.E. Downing, O.J. Kuik, and J.B. Smith, 2004: Distributional aspects of climate change impacts. *Global Environmental Change*, **14(3)**, 259-272.

Tonnang, H.E.Z., R.Y.M. Kangalawe, and P.Z. Yanda, 2010: Predicting and mapping malaria under climate change scenarios: the potential redistribution of malaria vectors in Africa. *Malaria Journal*, **9**, 111-120.

Tompkins, E.L., W.N. Adger, E. Boyd, S. Nicholson-Cole, K. Weatherhead, and N. Arnell, 2010: Observed adaptation to climate change: UK evidence of transition to a well-adapting society. *Global Environmental Change*, **20(4)**, 627-635.

Turner, W.R., B.A. Bradley, L.D. Estes, D.G. Hole, M. Oppenheimer, and D.S. Wilcove, 2010: Climate change: helping nature survive the human response. *Conservation Letters*, **3(5)**, 304-312.

UKCIP, 2011: *Making Progress: UKCIP & Adaptation in the UK*. UK Climate Impacts Programme (UKCIP), School of Geography and the Environment, at the University of Oxford, Oxford, UK, 99 pp.

UNDP, 2004: *Reducing Disaster Risk: A Challenge for Development*. United Nation Development Programme (UNDP), Bureau for Crisis Prevention and Recovery, New York, NY, USA, 146 pp.

UNDP, 2005: *Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies and Measures*. Cambridge University Press, New York, NY, USA, 258 pp.

UNDP, 2008: *Human Development Report 2007/8. Fighting Climate Change: Human Solidarity in a Divided World*. United Nations Development Programme (UNDP), Palgrave Macmillan, Houndmills, Basingstoke, Hampshire, UK and New York, NY, USA, 384 pp.

UNDP, 2010: *Gender, Climate Change and Community-Based Adaptation*. A Guidebook for Designing and Implementing Gender-Sensitive Community-Based Adaptation Programmes and Projects, United Nations Development Programme (UNDP), New York, NY, USA, 69 pp.

UNFCCC, 2006: *Technologies for Adaptation to Climate Change*. The United Nations Framework Convention on Climate Change (UNFCCC), UNFCCC Secretariat, Bonn, Germany, 38 pp.

UNFCCC, 2007: *Investment and Financial Flows to Address Climate Change*. The United Nations Framework Convention on Climate Change (UNFCCC), UNFCCC Secretariat, Bonn, Germany, 272 pp.

UNFCCC, 2010: *Synthesis Report on Efforts Undertaken to Assess the Costs and Benefit of Adaptation Options, and Views on Lessons Learned, Good Practices, Gaps and Needs*. UNFCCC Secretariat, Bonn, Germany, 13 pp.

UNFCCC, 2011: *Assessing the Costs and Benefits of Adaptation Options: An Overview of Approaches*. The Nairobi Work Programme and United Nations Framework Convention on Climate Change (UNFCCC), UNFCCC Secretariat, Bonn, Germany, 48 pp.

Urwin, K. and A. Jordan, 2008: Does public policy support or undermine climate change adaptation? Exploring policy interplay across different scales of governance. *Global Environmental Change*, **18(1)**, 180-191.

Van Aalst, M.K., T. Cannon, and I. Burton, 2008: Community level adaptation to climate change: the potential role of participatory risk assessment. *Global Environmental Change*, **18(1)**, 165-179.

Verner, D., 2012: Gender-responsive climate change adaptation: ensuring effectiveness and sustainability. In: *Adaptation to a Changing Climate in the Arab Countries: A Case for Adaptation Governance and Leadership in Building Climate Resilience* [Verner, D. (ed.)]. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, pp. 277-308.

Villamizar, A., 2011: Adaptación al Cambio Climático y políticas públicas: una deuda de alto riesgo para América Latina? *Mundo Nuevo*, **1(6)**, 301-338.

Webb, R. and J. Beh, 2013: *Leading Adaptation Practices and Support Strategies for Australia: An International and Australian Review of Products and Tools*. Synthesis and Integrative Research: Final Report, National Climate Change Adaptation Research Facility (NCCARF) and Australian National University, NCCARF, Griffith University Gold Coast Campus, Southport, Australia, 105 pp.

West, J.M. and D. Brereton, 2013: *Climate Change Adaptation in Industry and Business*. Synthesis and Integrative Research Final Report, National Climate Change Adaptation Research Facility (NCCARF), Griffith University Gold Coast Campus, Southport, Australia, 144 pp.

Westerhoff, L., E.C.H. Keskitalo, and S. Juhola, 2011: Capacities across scales: local to national adaptation policy in four European countries. *Climate Policy*, **11(4)**, 1071-1085.

Wheeler, D., 2011: *Quantifying Vulnerability to Climate Change: Implications for Adaptation Assistance*. CGD Working Paper 240, Center for Global Development (CGD), Washington, DC, USA, 49 pp.

Wolf, J., W.N. Adger, I. Lorenzoni, V. Abrahamson, and R. Raine, 2010: Social capital, individual responses to heat waves and climate change adaptation: an empirical study of two UK cities. *Global Environmental Change*, **20(1)**, 44-52.

World Bank, 2008: *The Pilot Program for Climate Resilience under the Strategic Climate Fund*. CTF-SCF/7 November 10, 2008, The World Bank, Washington, DC, USA, 7 pp.

World Bank, 2010: *World Development Report 2010: Development in a Changing Climate – Concept Note*. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 43 pp.

World Economic Forum, 2002: *2002 Environmental Sustainability Index.* An Initiative of the Global Leaders for Tomorrow Environment Task Force, World Economic Forum (WEF), Annual Meeting 2002, in collaboration with Yale Center for Environmental Law and Policy (YCELP), Yale University and Center for International Earth Science Information Network (CIESIN), Columbia University, YCELP, New Haven, CT, USA, 297 pp.

World Economic Forum, 2012: *Global Risks 2012*. 7th edn., An initiative of the Risk Response Network, World Economic Forum (WEF), Geneva, Switzerland, 62 pp.

WRI, 2009: *Bellagio Framework for Adaptation Assessment and Prioritization*. WRI Working Paper, World Resources Institute (WRI), Washington, DC, USA, 6 pp.

Wu, Q., G. Cheng, W. Ma, and Y. Liu, 2008: Railway construction techniques adapting to climate warming in permafrost regions. *Advances in Climate Change Research*, **4**, 60-66.

Yohe, G. and R.S.J. Tol, 2001: Indicators for social and economic coping capacity – moving toward a working definition of adaptive capacity. *Global Environmental Change*, **12(1)**, 25-40.

Young, H., A.M. Osman, A.M. Abusin, M. Asher, and O. Egemi, 2009: *Livelihoods, Power and Choice: The Vulnerability of the Northern Rizaygat, Darfur, Sudan*. Feinstein International Center, Tufts University, Medford, MA, USA, 115 pp.

Ziervogel, G. and A. Taylor, 2008: Feeling stressed: integrating climate adaptation with other priorities in South Africa. *Environment*, **50(2)**, 32-41.

15 Adaptation Planning and Implementation

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Mimura, N., R.S. Pulwarty, D.M. Duc, I. Elshinnawy, M.H. Redsteer, H.Q. Huang, J.N. Nkem, and R.A. Sanchez Rodriguez, 2014: Adaptation planning and implementation. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 869-898.

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Frequently Asked Questions

15.1: What is the present status of climate change adaptation planning and implementation across the globe? 876

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Executive Summary

Adaptation to climate change is transitioning from a phase of awareness to the construction of actual strategies and plans in societies (*robust evidence*, *high agreement*). The combined efforts of a broad range of international organizations, scientific reports, and media coverage have raised awareness of the importance of adaptation to climate change, fostering a growing number of adaptation responses in developed and developing countries. This represents major progress since the IPCC Fourth Assessment Report (AR4). The literature illustrates heterogeneity in adaptation planning related to the context specific nature of adaptation, but also to the differences in resources, values, needs, and perceptions among and within societies. However, it is not yet clear how effective these responses currently are and will be in the future. Few adaptation plans have been monitored and evaluated. There is a tendency in the literature to consider adaptation planning a problem-free process capable of delivering positive outcomes, underestimating the complexity of adaptation as a social process, creating unrealistic expectations in societies, and perhaps overestimating the capacity of planning to deliver the intended outcome of adaptation. {15.2.1-2}

The national level plays a key role in adaptation planning and implementation, while adaptation responses have diverse processes and outcomes at the subnational and local levels (*robust evidence*, *high agreement*). National governments assume a coordinating role of adaptation actions in subnational and local levels of government, including the provision of information and policy frameworks, creating legal frameworks, actions to protect vulnerable groups, and, in some cases, providing financial support to other levels of government. In the increasing number of adaptation responses at the local level in developed and developing countries, local agencies and planners are often confronted by the complexity of adaptation without adequate access to guiding information or data on local vulnerabilities and potential impacts. Even when information is available, they are left with a portfolio of options to prepare for future climatic changes and the potential unanticipated consequences of their decisions. Therefore, linkages with national and subnational levels of government, as well as the collaboration and participation of a broad range of stakeholders, are important. Steps for mainstreaming adaptation have been identified but challenges remain in their operationalization within the current structures or operational cultures of national, subnational, and local agencies. {15.2.1, 15.5.1}

Institutional dimensions in adaptation governance play a key role in promoting the transition from planning to implementation of adaptation (*robust evidence*, *high agreement*). While institutional dimensions may both enable and limit adaptation planning and implementation, the literature has so far mostly reported on how current institutional arrangements restrict the mainstreaming of climate adaptation. The most commonly emphasized barriers or enablers of institutional change in planning and implementation identified for both developing and developed countries are: (1) multilevel institutional coordination between different political and administrative levels in society; (2) key actors, advocates, and champions initiating, mainstreaming, and sustaining momentum for climate adaptation; (3) horizontal interplay between sectors, actors, and policies operating at similar administrative levels; (4) political dimensions in planning and implementation; and (5) coordination between formal governmental, administrative agencies, and private sectors and stakeholders to increase efficiency, representation, and support for climate adaptation measures. {15.2.2, 15.5.1}

Adaptation planning and implementation are dynamic iterative learning processes recognizing the complementary role of adaptation strategies, plans, and actions at different levels (national, subnational, and local) (*robust evidence*, *high agreement*). Climate change adaptation (CCA) takes place as a response to multiple stresses, which highlights the need of connecting CCA with development strategies and plans, and disaster risk management (DRM). The importance of CCA is influenced by how the issue is framed in particular contexts, and, to the extent that it is viewed as a public safety issue or a development issue, it has greater resonance within national and local policies. In many cases, the most attractive adaptation actions are those that offer development benefits in the relatively near term, as well as reductions of vulnerabilities in the longer term. There is a growing recognition in the literature that the linkages between adaptation, development, and DRM need to be more explicit targeting co-benefits among the societal goals. Considering adaptation planning and implementation learning processes can help carrying out periodic adjustments to accommodate changes in climate and socioeconomic conditions that can strengthen the role of planning as a societal tool for CCA and DRM. {15.2.1, 15.3.2-3, 15.5.1}

There is no single approach to adaptation planning because of the complex, diverse, and context-dependent nature of adaptation to climate change. Although top-down and bottom-up approaches are widely recognized, the actions in practice are combinations of these approaches (*medium evidence*, *high agreement*). The literature illustrates that the debate of climate change is dominated at

present by impacts-led approaches that focus on climate risks through the construction of defensive infrastructure rather than on human vulnerability. It is unclear at this point if these adaptation plans consider impact-led approaches just the start of an adaptation process rather than its culmination. Knowledge of impacts and vulnerabilities does not necessarily lead to the most cost-effective and efficient adaptation policy decisions. This is partly due to the uncertainty associated with future climate and socioeconomic conditions but also to the context specificity of adaptation. The literature suggests that coupling adaptive improvements in infrastructure with efforts to improve ecosystem resilience, governance, community welfare, and development improve community resilience. It also suggests combining top-down and bottom-up approaches strengthens adaptation planning and implementation. {15.2.1, 15.3.1, 15.3.3, 15.5.1.2, Box 15-1}

A variety of tools are being employed in adaptation planning and implementation depending on social and management context (*robust evidence*, *high agreement*). Uncertainties in climate change, coupled with the complexities of social-ecological systems, emphasize the need for a variety of tools in adaptation planning and implementation. Information and knowledge on climate change risks from various stakeholders and organizations are essential resources for making adaptation planning. Multidisciplinary efforts have been engaged to develop, assess, and communicate climate information and risk assessments across time scales. These efforts employ a mixed portfolio of measures, from simple agroclimate calendars to computerized decision-support tools. Although a wide range of adaptations are possible with current technologies and management practices, development and diffusion of technologies can expand the range of adaptation possibilities by expanding opportunities or reducing costs. Monitoring and early warning systems play an important role in helping to adjust and revise adaptation implementation, especially on the local scale. Innovative tools have also been developed, such as ecosytem-based adaptation and a range of insurance tools. {15.4}

15.1. Introduction

As impacts of climate change have become apparent around the world, adaptation has attracted increasing attention. The impacts are expected to be particularly severe in the developing world and among marginalized communities because of limited adaptive capacity. Adaptation is an important pillar for the response to climate change, and the IPCC Assessment Reports highlight the complementary roles of mitigation and adaptation in climate policy. Particularly, IPCC Fourth Assessment Report (AR4) (IPCC, 2007) provided an evaluation of adaptation that is the departure point for the present report. The AR4 emphasized that adaptation will be necessary to address impacts resulting from climate change that is already unavoidable due to past emissions. A wide array of adaptation options were noted, but also that the level of adaptation was inadequate for a reduction in vulnerability to future climate change. Moreover, the report showed there are barriers, limits, and costs that are not fully understood.

Since the publication of IPCC AR4, significant progress has been made on the adaptation activities both quantitatively and qualitatively. In particular, there is substantial progress in development of national adaptation strategies and plans. These include climate change adaptation (CCA) legislation and formal national strategies. As of 2012, 26 of the Organisation for Economic Co-operation and Development (OECD) countries have developed or are currently developing strategic frameworks for national adaptation (Mullan et al., 2013). Forty-nine least developed countries produced and submitted National Adaptation Programmes of Action (NAPAs) to the United Nations Framework Convention on Climate Change (UNFCCC) as of 2013. At the same time, the academic literature and reports from multilateral development agencies, international organizations, and non-governmental organizations (NGOs) document numerous cases of community-based activities for CCA in developing countries. Through these activities, a range of lessons are being learned, while barriers and limits are also emerging. The wider social dimensions of adaptation have also attracted more attention since AR4. As the diverse, complex, and context-specific nature of adaptation becomes apparent (differences in resources, values, needs, and perceptions among and within societies), the related areas expand in the wider social-ecological system, and the number of stakeholders increases. Based on this recognition, the importance of mainstreaming adaptation and the integration of adaptation policies within those of development increases.

Current research has expanded its focus to reflect these advances (Biesbroek et al., 2010). Until the mid-1990s, research on climate change focused almost exclusively on understanding of climate system dynamics and modeling of future climate. Several programs developed recently give prominence to studies of vulnerability and adaptive capacity, and associated adaptation options, measures, and strategies, including local, regional, and sectoral studies. As adaptation activities progress, many challenges have emerged, such as how to manage the decision-making process, how to develop strategies and plans, and how to implement them. In this regard, the roles within multilevel governance become an issue, such as horizontal coordination among different agencies and departments, and vertical coordination of various stakeholders from regional, national, to local actors. Furthermore, many countries face challenges in moving from the development of adaptation strategies and plans to implementation. These provide challenges for the research community as well.

There are many definitions and characteristics of adaptation strategies (Carter et al., 1994; Burton et al., 2005). For the purpose of this chapter, adaptation strategies are defined as a general plan of action for addressing the impacts of climate change, including climate variability and extremes. Such strategies include a mix of policies and measures that have the overarching objective of reducing vulnerability to climate change impacts. This chapter examines and evaluates the literature on CCA, in order to assess the progress made toward CCA and explore difficulties encountered in the implementation of adaptation plans. The IPCC Working Group II (WGII) Fifth Assessment Report (AR5) has four interrelated chapters about adaptation that discuss complementary aspects of the process (see Figure 14-1). This chapter focuses on the actions taken from international to local levels, in various sectors in order to assess (1) the recent status of CCA planning and implementation across the globe; (2) the characteristics of adaptation in different settings; (3) the strategies, approaches, and tools used in the adaptation practices; and (4) the governance of adaptation including building adaptive capacities. This chapter also draws attention to factors that motivate and facilitate the development of adaptation strategies, as well as how scientific and technical information, support, and collaborative mechanisms are utilized in the process.

15.2. Status of Adaptation Planning and Implementation

15.2.1. Adaptation Planning at Different Levels

15.2.1.1. Common Recognition and International Mechanisms

The combined efforts of a broad range of international organizations, scientific reports, and media coverage have raised awareness of the importance of adaptation to climate change since the publication of AR4. Adaptation is transitioning from a phase of awareness and promotion to the construction and implementation of plans, strategies, legislation, and projects at national, subnational, and local levels (Biesbroek et al., 2009; Preston et al., 2009; Tompkins et al., 2010; Berrang-Ford et al., 2011; Romero-Lankao and Dodman, 2011; Dodman, 2012). The review of the literature identifies a high heterogeneity of adaptation planning. There is significant heterogeneity in adaptation planning that is related to the context-specific nature of adaptation (differences in resources, values, needs, and perceptions among and within societies). This heterogeneity also results from different approaches among countries, multilateral development agencies, and international organizations that promote and fund adaptation, and from differences in knowledge, information, and awareness on adaptation alternatives across societies.

Although attention to climate change impacts and disaster risk management are key elements of adaptation, they appear to have a more prominent role in the early stages of planning and implementation (Few et al., 2007a; Hofstede, 2008; Mitchell et al., 2010; Garrelts and Lange, 2011; Harries and Penning-Rowsell, 2011; Rosenzweig et al., 2011; Rumbach and Kudva, 2011; Etkin et al., 2012; IPCC, 2012). Several authors express concern that a strong focus on impacts can overshadow

the analysis of the underlying stressors of hazards, neglecting the drivers of vulnerability, and thus limiting the effectiveness for interventions (Sabates-Wheeler et al., 2008; Boyd and Juhola, 2009; Orlove, 2009; Ribot, 2010; Rumbach and Kudva, 2011). This approach could obscure opportunities for connecting development pressures, poverty, social inequality, and climate change, particularly for the reduction of social vulnerability (Lemos et al., 2007; Hardee and Mutunga, 2010; Sietz et al., 2011). Furthermore, other scholars suggest that knowledge of impacts and vulnerabilities does not necessarily lead to the most cost-effective and efficient adaptation policy decisions (Hulme et al., 2009; Barnett and Campbell, 2010).

The importance of climate adaptation is also influenced by how the issue is framed. For example, to the extent that adaptation is viewed as a development issue (current development stressors and challenges; existing policy and existing agendas; and knowledge, risks, and issues communities already face), it may have greater resonance within local government (Ewing et al., 2008; Moser and Satterthwaite, 2008; Dovers, 2009; Hodson and Marvin, 2009; Stringer et al., 2009; Measham et al., 2010; Sanchez-Rodriguez, 2012). Multilateral development agencies encourage efforts in this direction through a number of guidelines, publication, and development assistance (UNDP, 2004; USAID, 2007; OECD, 2009; World Bank, 2010; UN-HABITAT, 2011a). Central to these efforts is the role of planning that connects adaptation to development needs and challenges (Blanco and Alberti, 2009; Dovers, 2009; Juhola and Westerhoff, 2011; Sanchez-Rodriguez, 2012). A critical issue commonly emphasized in the literature is the consideration of adaptation planning as a problem-free process capable of delivering positive outcomes. There is the risk of underestimating the complexity of adaptation planning as a social process, and it can lead to creating unrealistic expectations in societies, and overestimating the capacity of planning to deliver the intended outcome of preparing societies to adapt to the negative impacts of climate change. This highlights the importance of monitoring, evaluating, and reviewing adaptation planning and implementation (Adger et al., 2009b; Preston et al., 2009; Tompkins et al., 2010; Wolf et al., 2010).

The fast growth of international mechanisms for supporting adaptation planning has assisted in the creation of adaptation strategies, plans, and actions at the national, subnational, and local level. The directives and initiatives of the European Commission (EC) have fostered the creation of a large number of national adaptation strategies and plans in EU member countries since the last IPCC report (Biesbroek et al., 2009, 2010; Ford et al., 2011). Other relevant regional initiatives are the South Pacific Regional Environmental Programme (SPREP) supported by a number of international agencies, and in the Caribbean through the Caribbean Catastrophic Risk Insurance Facility (Pulwarty et al., 2010). The literature reports a growing number of mechanisms developed by multilateral development organizations, development cooperation agencies from developed countries, United Nations programs (UNDP, 2004, 2010a; UN-HABITAT, 2010, 2011a), multilateral development agencies (USAID, 2007; OECD, 2009; World Bank, 2010, 2011a; Abbas et al., 2012), and NGOs (ICLEI, 2008; IFRC et al., 2009; Pew Centre on Global Climate Change, 2009; Braman et al., 2010; ActionAid et al., 2012; Crane, 2013). These organizations focus on their particular geographic and thematic areas of interest in their support for adaptation planning. Particularly relevant are the activities of UNFCCC for least developed countries (LDCs) through the National Adaptation Programmes of Action (NAPAs) and for LDCs and other developing countries through the National Adaptation Plans (NAPs).

Key funding mechanisms are associated with the Global Environmental Facility (GEF) adaptation funds (Least Developed Countries Climate Adaptation Fund and Special Climate Change Fund), support for the Pilot Program for Climate Resilience (PPCR), and special purpose adaptation funds for UN agencies. The Adaptation Fund (AF) set up under the Kyoto Protocol has pioneered direct access mechanisms to developing countries, allowing countries to access essential funds without having to work through a multilateral development agency.

15.2.1.2. National Initiatives

The movement to introduce adaptation into national policies has accelerated in both developed and developing countries. These diverse national adaptation initiatives reflect the characteristics of the domestic political structures, socioeconomic conditions, values, and perceptions, as well as development stresses and opportunities. National governments are assuming a coordinating role in adaptation actions in subnational and local levels of government. National-level coordination includes the provision of information about potential risks, in order to strengthen actions of state and local governments. These activities provide policy frameworks that guide decisions at subnational levels, to spur and coordinate the creation of legal frameworks, to direct action in sectors and resources for national development (agriculture, fisheries, health, ecosystem protection, among others), to protect vulnerable groups, and to provide financial support to other levels of government (Hulme et al., 2009; Biesbrock et al., 2010; Birkmann and Teichman, 2010; Berrang-Ford et al., 2011; Westerhoff et al., 2011). National governments also facilitate the coordination of budgets and financing mechanisms (Alam et al., 2011; Kalame et al., 2011).

In recent years, Europe's creation of national adaptation strategies and plans has been particularly dynamic. Twelve European countries have created National Adaptation Strategies: Austria, Belgium, Denmark, Finland, France, Germany, Hungary, the Netherlands, Norway, Portugal, Spain, and UK (only two of them were created before the AR4—Finland and Spain) (Biesbroek et al., 2010). Moreover, some countries have programmed the evaluation of their national adaptation strategies because they recognize the need to learn from the adaptation process (UK, Germany, Australia, the USA, and Mexico, among others) (Bierbaum et al., 2013). Most strategies are regarded as the start of a policy process rather than its culmination, providing the important perspective of considering iterative evaluation as part of planning and implementation (Hulme et al., 2009; Biesbroek et al., 2011; Pulwarty et al., 2012).

The LDCs national adaptation responses—implemented through UNFCCC's NAPAs—provide data on efforts to link local level adaptation and development (Agrawal, 2008; Agrawal and Perrin, 2008; Stringer et al., 2009). More than 50% of the projects under this program are concentrated in three key sectors for development and livelihoods: food security, terrestrial ecosystems, and water resources. They attract the support of a greater range of actors, but some suggest that linkages between development and adaptation need to be made more explicit

(Stringer et al., 2009). Sustained monitoring, evaluation, and feedback that is needed to learn from the NAPAs process would help these countries transcend from a project-by-project effort to a more complete union of adaptation and domestic and local development. Assessment on NAPAs is also given in Section 14.4.4.

15.2.1.3. Subnational and Local Activities

Adaptation planning and implementation initiatives illustrate differences on the role of subnational governments in the governance structure of countries, from those with strong concentration of political and economic power to a very minor role in governance and decision making. Subnational governments often have a complementary role to national governments in adaptation planning that is reflective of the governance structure (Moser, 2005; West and Gawith, 2005; Lemmen et al., 2008; Karl et al., 2009; Pew Centre on Global Climate Change, 2009). Although guiding frameworks have not created for subnational governments in many countries, the states and provinces in some countries have an active role in CCA (Brekke et al., 2009; Dinse et al., 2009; Staples, 2011; Barsugli et al., 2012; Bierbaum et al., 2013; Mukheibir et al., 2013).

There is a significant increase in the number of planned adaptation responses at the local level in rural and urban communities of developed and developing countries since AR4. Climate adaptation is context dependent and it is uniquely linked to location, making it predominantly a local government and community level of action (Corfee-Morlot et al., 2009; Glaas et al., 2010; Mukheibir et al., 2013). Among these efforts are adaptation plans that utilize local knowledge. Local knowledge-based adaptation is focused primarily on the use of traditional knowledge to increase adaptive capacity at the community level, examples of which are shown in Table 15-1. In addition to raising adaptive capacity, local

Table 15-1 | Application of local knowledge in climate change adaptation.

Location	Sector	Approach and strategy	Adaptive action implemented	Institutions	References
Southern Kimberley, Australia	Water supplies	• Define vulnerabilities • Increase adaptive capacity	• Compile observed changes • Increase monitoring • Manage water resources • Review TEK[a]	Universities; NGOs;[b] United Nations University	Green et al. (2010); Prober et al. (2011); Leonard et al. (2013)
Trinidad, Bolivia and northern central Bolivia	Ecosystems, agriculture	Reduce vulnerability	• Revive "camellones" (earthen platforms) TEK • Reduce erosion • Document local observations	Oxfam International; NGOs; Bolivian government; Food and Agriculture Organization	Oxfam International (2009)
Pinoleville Pomo Nation (California, USA)	Infrastructure	• Mitigation: solar power • Increase adaptive capacity	• Co-design infrastructure • Address insufficient capital • Address water shortages and energy needs	Universities; NGOs; Housing and Urban Development	Shelby et al. (2012); Pinoleville Pomo Nation Housing flyer (2013); Redsteer et al. (2013)
Fiji	Ecosystems and water supply	• Define vulnerabilities • Increase adaptive capacity	• Recognize TEK • Enable adaptive decision making • Enhance community awareness • Participate in development	Australian Agency for International Development; Fiji Department of Environment; University of the South Pacific	Dumaru (2010)
Kenya, Tanzania, Malawi, Zimbabwe, southern Zambia	Agriculture	• Define vulnerabilities • Increase technical capacity • Increase adaptive capacity	• Use drought early warning • Apply TEK • Develop novel reporting • Compile observed changes • Harvest rainwater • Change tilling practices • Use appropriate crop varieties	University of Capetown; University of Nairobi; the United Kingdom's Department for International Development; Canada's International Development Research Centre	Chang'a et al. (2010); Mugabe et al. (2010); Kalanda-Joshua et al. (2011); Majule et al. (2013); Masindel et al. (2013)
Reservation lands (western USA)	Health, water supplies, environment	• Define vulnerabilities and impacts • Increase adaptive capacity	• Compile observed changes • Utilize environmental legislation • Review indigenous knowledge • Analyze local meteorological data • Analyze historical/legal context • Increase monitoring	Universities and affiliated NGOs; tribal offices; federal agency research	Redsteer et al. (2010); Doyle et al. (2013); Gautam et al. (2013)

[a]TEK = Traditional ecological knowledge: adaptive ecological knowledge developed through an intimate reciprocal relationship between a group of people and a particular place over time.

[b]NGO = Nongovernmental organization.

Frequently Asked Questions

FAQ 15.1 | What is the present status of climate change adaptation planning and implementation across the globe?

Climate change adaptation has been receiving increasing attention as a result of recent media coverage and reports. Since the publication of the IPCC Fourth Assessment Report (AR4), a large assortment of adaptive actions has taken place in response to observed climate impacts. These actions mostly address sectoral interests, such as agricultural practices (e.g., altering sowing times, crop cultivars and species, and irrigation and fertilizer control), public health measures for heat-related risks (e.g., early warning systems and air pollution control), disaster risk reduction (e.g., early warning systems), and water resources (e.g., supply and demand management). Some of these are "autonomous" actions in a specific sector.

Another area where progress has been made since AR4 is the development of broad national-level plans and adaptation strategies. These have now been established in developed and developing countries worldwide. Because adaptation policy requires decision making amid uncertainties about future climate change and its impacts, the major pillars of adaptation plans are iterative assessment, flexible and adaptive planning, and enhancement of adaptive capacity. Adaptation plans are being developed and documented at the national, subnational, and community levels and by the private sector; however, there is still limited evidence of adaptation implementation. Implementation remains challenging because in the transition from planning to implementation the many interested parties must overcome resource, institutional, and capacity barriers. The difference in time scales between medium- and long-term adaptation plans and pressing short-term issues poses a significant problem for prioritizing adaptation.

In parallel with national-level planning, community-based adaptation (CBA) has become an increasingly prevalent practice, particularly in developing counties. It is increasingly apparent that CBA potentially offers ways to address the vulnerability of local communities by connecting climate change adaptation to non-climate local needs. Cities and local governments have also begun active engagement in climate change adaptation. Local governments play an important role in adaptation because they directly communicate with affected communities. For the past several years, leading practices have begun in New York City, Mexico City, Toronto, Albay Province in the Philippines, and elsewhere. These achievements were possible because of elected and local leadership; cooperation among national and local governments, private sectors, and communities; and the participation of boundary organizations, scientists, and experts.

knowledge often highlights vulnerabilities and impacts that may not be well known, especially when the areas where local knowledge is still held are remote and poorly monitored (e.g., Majule et al., 2013).

Indigenous communities are those populations that have cultural and historical ties to specific homelands. They are generally distinct from politically dominant populations (Battiste, 2008). Because of these characteristics, they are particularly vulnerable to climate change impacts. When assessing indigenous vulnerability and developing CCA strategies and resilience to climate change, the following issues need to be examined and addressed: the relationship of indigenous peoples to land, the degree of migration or displacement of indigenous communities (Miron, 2008), and their adaptive capacity. Vulnerability and challenges to adaptation for indigenous people are discussed broadly in Chapters 13, 27, and 28.

Local councils and planners are often confronted by the complexity of adaptation without adequate access to guiding information or data on local vulnerabilities and potential impacts. Even when information is available, they are left with a portfolio of options to prepare for future climatic changes but without effective guidance on decision making and the potential for unanticipated consequences arising from those decisions (Wilson, 2006; Storbjörk, 2007; Patt and Schröter, 2008; Urwin and Jordan, 2008; Gupta et al., 2010; Mathew et al., 2012; Rodima-Taylor et al., 2012; Mukheibir et al., 2013).

Local governments play a central role addressing the challenges of adaptation planning and implementation (Blanco and Alberti, 2009; Sanchez-Rodriguez, 2009; Rosenzweig and Solecki, 2010; Simon, 2010; Matthews, 2012). However, scholars stress the important role of partnerships among public, civic, and private sectors in CCA (Berkhout et al., 2006; Agrawal, 2010; Tompkins et al., 2010; Howe, 2011; Tompkins and Eakin, 2012). Inclusive and participatory approaches in adaptation planning at the local level are encouraged by international organizations (UNDP, 2004, 2010a; Moser, 2008; Moser and Satterthwaite, 2008; Ensor and Berger, 2009; Geiser and Rist, 2009; World Bank, 2010; Ford et al., 2011; UN-HABITAT, 2011a).

Urban areas are also the locus of a growing number of planning initiatives (Revi, 2008; Roberts, 2008; Stren, 2008; Blanco and Alberti, 2009; Hamin and Gurran, 2009; Hardoy and Pandiella, 2009; Lowe et al., 2009; O'Demsey, 2009; Parzen, 2009; Sanchez-Rodriguez, 2009; Tanner et al.,

2009; Corfee et al., 2010; Rosenzweig and Solecki, 2010; Simon, 2010; City of New York, 2011; City of Rotterdam, 2011; Romero-Lankao and Dodman, 2011; Rosenzweig et al., 2011; Carmin et al., 2012; Matthews, 2012). The primary determinant in creating adaptation plans has been a response to current climate extremes as well as potential future impacts (Rosenzweig and Solecki, 2010; Rosenzweig et al., 2011; Carmin et al., 2012). The difference in approaches has implications for adaptation governance, institutional arrangements, resources, and stakeholders' involvement in the planning and implementation processes. Understanding how these approaches work merits further analysis. Enforcing parallel agendas for DRM and CCA runs the risk of duplicating efforts and resources, creating competing actions and potential conflicts with unintended negative consequences, including maladaptation. Institutional arrangements would need to bridge the divide between CCA and DRM, particularly in terms of legislation, operational and management structures, working agendas, and time horizons (Schipper and Pelling, 2006; Birkmann and Teichman, 2010; Falaleeva et al., 2011).

15.2.2. Adaptation Implementation

There is a minority of academic literature that provides information on the implementation of adaptation plans, in contrast with the large accumulation of literature that discusses concepts, strategies, and plans of adaptation. Projects and cases of adaptation, including those implemented, are presented mainly in reports from international organizations, multilateral development organizations, national and subnational governments, and NGOs (e.g., UNFCCC, 2011; Mullan, 2013). In addition, the sectoral and regional chapters in this report have segments that discuss adaptation planning and implementation and that provide an additional database of sectors and practices. Therefore, this section assesses the status of adaptation implementation based on these chapters in addition to other literature.

Adaptation practices reflected in the WGII AR5 include agriculture, public health for heat-related risks, disaster risk reduction, water resources, coasts, and urban areas, among others. Options and approaches used in implementation vary widely, ranging from traditional and existing to new and innovative measures. For example, farmers have been adapting to climate change worldwide, and current common practices include altering sowing times, crop cultivars and species, or irrigation and fertilizer control (Fujisawa and Koyabashi, 2010; Lasco et al., 2011; Olesen et al., 2011); reduced tillage practices; and technical measures to more effectively capture rainwater and reduce soil erosion (Thomas et al., 2007; Marongwe et al., 2011; see also Sections 7.5.1, 22.4.5.7, 23.4.1, 24.4.4.5, 27.3.4.2). These have proven to be effective in many cases, while some measures faced other problems; for example, earlier sowing is often prevented by lack of soil workability and frost-induced soil crumbling (Oort, 2012). Furthermore, simple options such as changes in sowing and harvesting dates may become less successful in a more variable climate (Moriondo et al., 2010; see also Section 23.4.1). Adaptation in agriculture is also linked with water management. Adaptation to water scarcity can be improved by taking into account a set of agronomic practices and irrigation such as deficit irrigation (Geerts and Raes, 2009; see also Section 27.3.4.2). For public health for heat-related risks, major approaches are developing early warning systems and air pollution control. According to Chapter 11 on Human Health, some studies report that heat wave early warning systems are effective to reduce heat-related mortality, resulting in fewer deaths during heat waves after implementation of the system (e.g., Ebi et al., 2004; Tan et al., 2007; Fouillet et al., 2008). A national assessment attributed the lower death toll to greater public awareness of the health risks of heat, improved health care facilities, and the introduction in 2004 of a heat wave early warning system (Fouillet et al., 2008; see also Section 11.7.3).

Mullan (2013) indicated that implementation of adaptation plans are still at an early stage despite the rapid development of strategies and plans that have occurred in OECD countries. In many sectors, adaptation to both environmental conditions and climate change includes accumulating traditional experience and knowledge for adaptation. Furthermore, each country has also developed its own policies and options to prevent, cope with, mitigate, and utilize various environmental changes. As the occurring adaptive actions are usually based on such existing knowledge and options, they are incremental. Research has shown that local governments that have started implementing adaptation plans mostly tend to adopt a reactive or event-driven approach to adaptation relying on technical measures. Often the focus is on climate variability and current weather extremes rather than long-term climate change (Næss et al., 2005; Tompkins, 2005; Wall and Marzall, 2006; Crabbé and Robin, 2006; Storbjörk, 2007; Blanco and Alberti, 2009; Amundsen et al., 2010; Glaas et al., 2010; Anguelovsky and Carmin, 2011; Measham et al., 2011; Preston et al., 2011; Dannevig et al., 2012; Romero-Lankao et al., 2012; Runhaar et al., 2012). Climate adaptation efforts reported on at present are often piecemeal and fragmented approaches, dealing with partial solutions and approaches to climate adaptation, rather than more full-scale implementation (Granberg and Elander, 2007; Blanco and Alberti, 2009; Bulkeley et al., 2009; Amundsen et al., 2010; Burch, 2010; Tompkins et al., 2010; Preston et al., 2011; Dannevig et al., 2012; Mees et al., 2012; Romero-Lankao, 2012; Runhaar et al., 2012). In many cases, these practices have been embedded in existing policies, and thus not necessarily framed or made visible as climate adaptation actions (Tompkins et al., 2010; Berrang-Ford et al., 2011; see Box 25-5). It should be noted that several of these reports on local climate adaptation actions have been taking place without explicit regulative demands for climate adaptation.

A particular challenge is implementation of local and short-term decisions in the context of long-term climate information. Improving the use of climate risk information across time scales, especially in the context of early warning systems, has helped bridge these gaps (van Aalst, 2009; IPCC, 2012; Pulwarty and Verdin, 2013). Independent from the growing attention for extremes in CCA, there has also been a shift in disaster risk management policy and practice, aiming to shift the balance of attention and expenditure from disaster response and reconstruction to disaster risk reduction and building resilience (not limited to climate-related extreme events).

There is growing awareness of the need for ecosystem-based, institutional, and social measures, although engineered and technological adaptation options are the most common adaptive responses (see Box CC-EA). A feature captured in WGII AR5 is that integrated approaches have been pursued in many areas such as integrated water resource management

and integrated coastal management (see Table 3-3; Sections 8.3.3.4 and 23.7.2 for water; Section 5.5.4 for coasts). These integrated policies aim at addressing multiple objectives including CCA, development, and disaster risk reduction. For example, the U.S. Water Utilities Climate Alliance (WUCA, 2010) provides a comprehensive overview of ways of delivering water management which incorporates climate change and its uncertainty. Climate change has been incorporated into water resources planning in England and Wales (Arnell, 2011; Wade et al., 2013) and in the Netherlands (de Graaff et al., 2009). Guidance has been also developed on the inclusion of adaptation in water management (UNECE, 2009) and river basin management plans (EC, 2009b; see also Section 23.7.2). Many sectors promote adaptive management in CCA to improve flexibility in its implementation.

Targets of early adaptation are focused on capacity building within governments and communities. These important first steps include increasing awareness of the risk of climate change, access to scientific information, development of common goals, and creation of operational institutions, which are important premises for adaptation. Capacity building itself is often a target of adaptation implementation, particularly in developing countries (e.g., van Aalst et al., 2008; Simões et al., 2010; UNFCCC, 2013; see Table 15-1 for capacity building cases). There are many factors to promote or hinder the implementation of adaptation; Table 15-2 provides examples where the drivers and motivations for transition to implementation are highlighted. Section 15.5 provides an analysis of the role of institutional dimensions for both planning and implementation of adaptation.

15.2.3. Financing for Adaptation

Adapting to the impacts of climate change requires the mobilization of a significant amount of funding for adaptation measures in a wide range of sectors. A number of studies suggest that the annual amount of adaptation funding needed by developing countries by 2030 is on the order of several tens of billions of dollars (e.g., UNFCCC, 2007;

Frequently Asked Questions

FAQ 15.2 | What types of approaches are being used in adaptation planning and implementation?

Adaptations employ a diverse portfolio of planning and practices that combine subsets of:

- Infrastructure and asset development
- Technological process optimization
- Institutional and behavioral change or reinforcement
- Integrated natural resources management (such as for watersheds and coastal zones)
- Financial services, including risk transfer
- Information systems to support early warning and proactive planning.

Although approaches vary according to context and the level of government, there are two general approaches observed in adaptation planning and implementation to date: top-down and bottom-up. Top-down approaches are scenario-driven and consist of localizing climate projections, impact and vulnerability assessments, and formulation of strategies and options. National governments often take this approach. National adaptation strategies are increasingly integrated with other policies, such as disaster risk management. These tendencies lead to adaptation mainstreaming, although there are various institutional barriers to this process. As the consideration of the social dimensions of climate change adaptation has attracted more attention, there has been an increased emphasis on addressing the needs of the groups most vulnerable to climate change, such as children, the elderly, disabled, and poor. Bottom-up approaches are needs driven and include approaches such as community-based adaptation (CBA). CBA is often prominent in developing countries, but communities in developed countries also use this approach. Where a combination of top-down and bottom-up activities has been undertaken, the links between adaptation planning and implementation have been strengthened. In either approach, participation by a broad spectrum of stakeholders and close collaboration between research and management have been emphasized as important mechanisms to undertake and inform adaptation planning and implementation.

Local governments and actors may face difficulties in identifying the most suitable and efficient approaches because of the diversity of possible approaches, from infrastructure development to "softer" approaches such as integrated watershed and coastal zone management. National and subnational governments play coordinating roles in providing support and developing standards and implementation guidance. Therefore, multilevel institutional coordination between different political and administrative levels is a crucial mechanism for promoting adaptation planning and implementation.

Table 15-2 | Transition from planning to implementation.

Scale	What is being implemented and why	Transition from planning to implementation	Monitoring and evaluation
Village of Kaslo (British Columbia) and surrounding unincorporated rural areas (Regional District of Central Kootenay (RDCK) Electoral Area D). Implemented 2010–2012. (Kaslo and Regional District of Central Kootenay Partnership, 2010)	The Village of Kaslo and RDCK Electoral Area D developed a Climate Adaptation Action Plan and identified water supply as a key community vulnerability related to projected climate change. Action plan noted that current demand for water almost equaled supply and observed the very limited data on water supply for creeks that supply water for the community.	The Village of Kaslo and RDCK Electoral Area D brought in experts in fields related to climate change impacts and involved extensive public outreach and engagement. Adaptation planning process identified projected changes in stream freshet and stream flows associated with climate change could result in insufficient water supply. Community leaders working through the Kaslo and District Community Forest Society sought funds to establish stream flow monitoring stations and developed a monitoring framework on key creeks to track changes in flows providing water to communities within Kaslo and RDCK Area. The Columbia Basin Trust contributed funding to this effort as part of follow-up to its support of the initial climate change planning process.	Monitoring and evaluation performed by Columbia Basin Trust's Communities Adapting to Climate Change Initiative. Electoral Area D Advisory Planning Commission monitors the implementation of action recommendations.
National Framework on Local Adaptation Plans for Action (LAPAs), Nepal. Implementation began in 2011. (Government of Nepal, 2011)	Nepal adopted the LAPA in 2011, becoming the first country to promote a bottom-up approach to adaptation planning and implementation. The National Adaptation Plan for Action and the National Climate Change Policy state that at least 80% of the available budget will go toward directly implementing adaptation actions at the local level. To date, 70 LAPAs have been prepared (69 at the village administrative scale and 1 within a municipality) and are under implementation by vulnerable communities.	Policy makers recognized the need to integrate local and context specific adaptation plans into local to national adaptation planning as a way to ensure robust climate change adaptation planning and implementation. The Ministry of Science, Technology and Environment and the Ministry of Federal Affairs and Local Development played a leadership role at the central level in coordinating the development and implementation of LAPAs.	Monitoring and evaluation play key roles in supporting iterative planning. Financial arrangements play a key role in integrating local adaptation options into development planning processes. Adaptation investments are being costed and integrated into annual and medium-term budget frameworks and resource mobilization strategies. Nepal's budget for fiscal year 2013/14 has included Climate Change Financing Code, and of the total budget, 5.36% is directly related to climate change financing.
Local government, the Albay Province, Philippines. Implementation began in 2008. (Lasco et al., 2009)	The Albay Declaration on Climate Change Adaptation specified mainstreaming climate change into local and national development policies. The Albay Integrated Agricultural Rehabilitation Program established farm clusters to assist farmers and fisher folk in their agricultural, food, technological, and training needs.	Program planning began in December 2006 after Typhoon Reming's devastation. The plan prevents scarcity of agricultural commodities, accelerates food production, pump-primes the agricultural industry in the province, and speeds up rehabilitation of upland agricultural areas in Albay. The provincial government of Albay established the Center for Initiatives and Research on Climate Adaptation in 2008, a living research and training institution in collaboration with the Environment Management Bureau, World Agroforestry Centre, Bicol University, and the University of the Philippines Los Baños. Local champions such as the Governor committed time and resources to put climate change on the provincial agenda and also on the national development and policy agenda, addressing the needs of farmers and fisher folk.	Main mechanism for institutional and stakeholder collaboration is through the Inter-Agency Committee on Climate Change Philippine Senate Resolution No. 191, passed during 14th Congress, 1st regular session, adopting the Albay Declaration on Climate Change Adaptation as a framework. Mainstreaming of global warming concerns gives a voice to the Albay Declaration in Congress and directly encourages policymakers to mainstream climate change in policymaking; and indicators measure a cleaner environment for the community, improvement of infrastructure development plans, land development/conversion activities, institutionalization of pre-planning, enhanced implementation, and enhanced monitoring and evaluation.
Pilot Program on Climate Resilience (PPCR), 2009. (CIF, 2012; PPCR, 2013)	Phase I (planning): supported by multilateral development bank partners, in 2 years a strategic plan was developed consistent with national development objectives. Phase II (implementation): countries define "transformational change" in the context of their national circumstances. Scaling up potential of successful pilots (e.g., use of good practices in Bangladesh). Addressing basic needs (e.g., food security in Niger). Mobilization of large-scale resources for investments (e.g., coastal highways in Samoa). Country leadership capacity dependent on experience with integrating climate change into planning activities, institutional and human capacities, and need to respond to emergencies. Recent climate extreme related disasters have affected development.	The capacity of countries to take on a leadership role depended on their prior experience with integrating climate change considerations into planning activities, their institutional and human capacities, and their demands to respond to other emergencies. The strategic plans drew on National Adaptation Plans for Action, national climate change strategies (if they existed), and national development strategies and plans. Lead agency roles assigned to planning or finance ministries (e.g., Zambia, Samoa) or environment-related ministries (e.g., Bangladesh). Disaster risk management units included. Coordinate the work of donors and/or leverage non-PPCR resources. For example, Cambodia and Zambia have leveraged co-financing from the International Fund for Agricultural Development and the Nordic Development Fund, respectively.	The framework includes five core indicators designed to measure outcomes at the country level, aggregated from individual PPCR components. These are (1) number of people supported by the PPCR to manage the effects of climate change; (2) degree of integration of climate change in national, including sector, planning; (3) extent to which vulnerable households, communities, businesses, and public sector services use improved PPCR-supported tools, instruments, strategies, and activities to respond to climate vulnerability and climate change; (4) evidence of strengthened government capacity and coordination mechanisms to mainstream climate resilience; and (5) quality of and extent to which climate-responsive instruments/investment models are developed and tested. All of the core indicators address gender issues either directly or indirectly.

Continued next page →

Table 15-2 (continued)

Scale	What is being implemented and why	Transition from planning to implementation	Monitoring and evaluation
United Kingdom National Adaptation Programme. Implemented in 2012. (UK HM Government, 2013)	Pursuant to the Climate Change Act 2008, the Climate Change Risk Assessment (CCRA) 2012 for the UK brought together the best available evidence, using a consistent framework to identify the risks and opportunities related to climate change. The assessment distilled approximately 700 potential risks down to more than 100 for detailed review. Recent extreme weather in Britain, such as the flooding in the winter of 2012 and the drought of early 2012, brought into sharp relief the importance of anticipating and managing weather extremes. Costs of rebuilding and impacts on essential public services highlighted the need for implementing preparedness and adaptation.	The Climate Ready Support Service provides direct support and online information to help organizations assess their sensitivity to a changing climate and take steps to manage their climate risks. Through the Service the Environment Agency is working with partners in priority sectors to provide tailored tools, guidance, and training to enable them to understand and respond to the challenges of a changing climate. Established partnerships are with the Met Office, the Local Government Association, Climate UK, and the Climate Change Partnerships. The government is also supporting the building of networks of organizations that may share common risks, e.g., the Infrastructure Operators Adaptation Forum.	Progress indicators provide iterative measures of progress to develop the next CCRA: • Process-based markers, such as whether planned policies have been implemented; • Quantitative data, such as statistics on trends in factors that influence risks from flooding and water scarcity. These provide a strong foundation for assessing overall adaptation in relevant areas. Discussions about the most appropriate framework are continuing. The Adaptation Sub-Committee of the Committee on Climate Change under the Climate Change Act assesses progress toward implementation of objectives, proposals, and policies highlighted in this report and the Register of Actions, with assessments published in 2015 and every 2 years hence.

World Bank, 2010; Smith et al., 2013). However, the annual costs could potentially range into the hundreds of billions of dollars (Parry et al., 2009). The differences between these estimates highlight the high degree of uncertainty in how they are derived. Key factors that contribute to this uncertainty include differences in the sets of sectors that are included in the analyses and the analytical methodologies used; uncertainties related to future climate changes and how best to adapt to them; and the lack of an agreed on operational definition of adaptation (e.g., Fankhauser and Burton, 2011; Christiansen et al., 2012; Naidoo et al., 2012; Smith et al., 2013).

Adaptation financing broadly refers to resources that are deployed to support climate-resilient development (World Bank Group, 2011). Funding for adaptation can be mobilized through a range of international and domestic, public and private financing mechanisms, and can take various forms (e.g., loans and grants). Public financing sources are typically used to support projects in the infrastructure sectors, where returns on investments (ROIs) are usually less attractive to private investors. Sources of public financing for adaptation include contributions from national budgets, multilateral and bilateral development funds, and UNFCCC operational funds—the Adaptation Fund, the Least Developed Countries Fund, and the Special Climate Change Fund (Christiansen et al., 2012; Haites and Mwape, 2013; Romani and Stern, 2013). A potentially key source of future public financing for adaptation is the Green Climate Fund that was officially designated at the 17th Conference of the Parties to the UNFCCC in Durban, but is not yet operational.

Examples of ongoing work targeting challenges in priority adaptation themes in several countries are provided by the Climate Change and Water Resources program at the Inter-American Development Bank. The lessons learned from emerging adaptation experiences are, first, that infrastructure investments (e.g., dams, levees, canals) remain critical for climate adaptation and reducing vulnerability to climate and weather-related events; and, second, that infrastructure investments need to be complemented by previously neglected investments in soft infrastructure (e.g., watershed management, land use planning and information, and stakeholder engagement). Efforts are also being supported by other regional development banks; for example, the Climate Adaptation for Rural Livelihoods and Agriculture (CARLA) project is supported by the African Development Bank Group).

Adaptation measures that offer reasonably predictable ROIs that are comparable to the returns on investments for non-adaptation measures with similar risk profiles have more opportunities to receive private financing (Christiansen et al., 2012). The fisheries and agriculture sectors, where operations are often locally owned, are examples of sectors that typically draw relatively high proportions of private financing in developing countries (often from domestic sources). Sources of private financing for adaptation traditionally include a range of financial institutions, such as international banks, multinational corporations, private equity and pension funds, insurance companies, and sovereign wealth funds. Charitable foundations and social investors are also sources of private financing for adaptation; compared to the financial institutions, these sources are often more motivated to provide financing for measures that generate lower ROIs (Christiansen et al., 2012).

Private financing for adaptation is primarily of two types: debt and equity. Debt-based financing typically consists of loans (e.g., bank loans) or bonds that must be paid back over time with interest. Equity-based financing generally involves a transfer of ownership rights through stocks or other assets. Export credits and foreign direct investment are two additional potential forms of private financing for adaptation. Export credits include guarantees, insurance, and other support that can help make developing country exports more competitive on the global market. Foreign direct investment is seen as having only limited potential for adaptation financing because it is highly concentrated in a few sectors and in a limited number of countries (Christiansen et al., 2012).

In both the public and private arenas, financing for adaptation is currently substantially less than financing for mitigation. According to an assessment of the total amount of climate finance available in 2009/2010 by Buchner et al. (2011), financing for mitigation outpaced financing for adaptation by a ratio of more than 20:1; whereas US$93 billion was provided for mitigation measures, only US$4.4 billion was directed to adaptation measures. Buchner et al. (2011) also noted that the vast majority (approximately 90%) of adaptation financing during

that period came from public sources, primarily bilateral institutions. Private adaptation financing remains limited owing to market, institutional, and policy barriers that depress ROIs on these activities (World Bank Group, 2011). However, public-private partnerships that use public financing to leverage private investment are currently used to fund projects in several climate-sensitive sectors, such as infrastructure in the energy, transport, and water and sewage sectors (World Bank, 2011b; World Bank Group, 2011). These partnerships are not necessarily focused on climate adaptation, but can serve as models for future adaptation projects.

15.3. Strategies and Approaches

15.3.1. Diverse Strategies and Mixed-Portfolio Approaches

Strategies and approaches in adaptation planning and implementation vary according to context and level of government. National plans assume a coordinating role in adaptation actions for subnational and local levels of government, providing policy frameworks that guide decisions at the subnational level, spurring and coordinating the creation of legal frameworks, and directing action in key sectors for national development (Biesbroek et al., 2010; Bierbaum et al., 2013; see also Section 15.2.1). Subnational governments often have a complementary role to national governments by reflecting the governance structure in each country (West and Gawith, 2005; Lemmen et al., 2008; Karl et al., 2009; Pew Centre on Global Climate Change, 2009). States and provinces in a number of countries have begun to have an active role in CCA (Dinse et al., 2009; Staples, 2011; Barsugli et al., 2012; Bierbaum et al., 2013; Mukheibir et al., 2013).

In contrast, local level strategies are more diverse because climate change impacts occur locally and adaptation is context dependent. The scale of community engagement and the approaches used may provide key elements for the success of adaptation programs (Patt and Schröter, 2008; Ensor and Berger, 2009; Ford et al., 2011; Pelling, 2011; Picketts et al., 2012). Methodological guidelines for community adaptation plans and actions fostered by international organizations emphasize strategies focused on the use of local and traditional knowledge to increase adaptive capacity at the community level (IFRC et al., 2009; IISD, 2012; Crane, 2013). Moreover, community adaptation planning has been strengthened through the use of geographic information systems (GIS), modeling, climate change scenarios, ecosystem services, and other scientific research methods applied to foster the ability of the community to design adaptation (Shaw et al., 2009; Bardsley and Sweeney, 2010; IAPAD, 2010). Multilateral development agencies recognize the importance of inclusive approaches for adaptation planning and implementation, but they tend to focus on strengthening the role of local governments (USAID, 2007; OECD, 2009; Bizikova, 2010b; UNDP, 2010b; UN-HABITAT, 2011b; World Bank, 2011a; Abbas et al., 2012).

The diversity of approaches for local adaptation fosters opportunities for creating and strengthening adaptation planning and its implementation. But local governments and actors can face difficulties in making sense of such a diversity of approaches and identifying the most suitable and efficient approaches to follow, as mentioned in Section 15.2.1. Lessons learned from the DRM experiences illustrate that a lack of coordination occurs among the strategies taken to reduce the risk of disaster at the local level (ISDR et al., 2010; ISDR, 2011). Local CCA strategies can face similar problems. To be effective, local governments and actors critically identify, select, and combine the strengths of diverse approaches. The coordinating role of national and subnational governments can provide support in this direction. However, multilevel institutional coordination between different political and administrative levels in society can be an institutional barrier to planning and implementation in developed and developing countries (Few et al., 2007b; Urwin and Jordan, 2008; Corfee-Morlot et al., 2009; Keskitalo, 2009; Pahl-Wostl, 2009; Measham et al., 2011; Robinson and Berkes, 2011; Sietz et al., 2011; Rodima-Taylor et al., 2012; Nilsson et al., 2012; Glaas and Juhola, 2013). There appear to be few national guidelines to assist local governments in selecting relevant approaches (Storbjörk, 2007; Glaas et al., 2010; Mozumder et al., 2011; Adhikari and Taylor, 2012; Carmin et al., 2012; Hedensted Lund et al., 2012; Peach Brown et al., 2013). Similar barriers have been reported in DRM (ISDR et al., 2010; ISDR, 2011). A combination of top-down and bottom-up activities may strengthen local adaptation planning and implementation (Urwin and Jordan, 2008; Bulkeley et al., 2009; Preston et al., 2013). Connecting adaptation planning strategies and local development needs and plans (USAID, 2007; OECD, 2009; Bizikova et al., 2010b; UNDP, 2010a; UN-HABITAT, 2011b; World Bank, 2011a; Abbas et al., 2012) and the use of low-regret strategies can also support local adaptation strategies and their implementation (Hallegatte, 2009; UNDP, 2010a).

15.3.2. Adaptation and Disaster Risk Management

The UN Hyogo Convention (2005–2015) has fostered the creation of a significant number of disaster risk management (DRM) plans and actions at the national and local level in developed and developing countries (ISDR, 2011). The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) (IPCC, 2012) highlighted the complementary aspects and differences between DRM and CCA. Measures that provide benefits under current climate and a range of future climate change scenarios, called low-regrets measures, have been identified as starting points for addressing projected trends in exposure, vulnerability, and climate extremes in national and regional adaptation plans (see Section 8.3.2.2). These measures have the potential to offer benefits now and lay the foundation for addressing projected changes. Furthermore, the evaluation of DRM implementation helps to strengthen CCA because climate change impacts and DRM are key elements of adaptation and have a prominent role in these early stages of CCA (Few et al., 2007b; Hofstede, 2008; Mitchell et al., 2010; Garrelts and Lange, 2011; Harries and Penning-Rowsell, 2011; Rosenzweig et al., 2011; Rumbach and Kudva, 2011; Etkin et al., 2012; IPCC, 2012).

DRM includes managing hazards from extreme weather events and helps communities to deal with the uncertainty of climate change (Mitchell et al., 2010). On the other hand, disaster risk management strategies often fail to account for the differing spectrum of threats, and time and spatial scales needed to address the root causes of climate change vulnerability and open opportunities for CCA (Etkin et al., 2012). Proponents of merging DRM with CCA stress the mutual benefits of this approach. They also note that, currently, CCA and disaster risk reduction

are within separate agencies, although they share similar objectives and challenges that can duplicate efforts if there is not an effort towards better coordination and integration (USAID, 2007; IFRC et al., 2009; Bizikova et al., 2010a; UNDP, 2010b; UN-HABITAT, 2011b; Abbas et al., 2012; EIRD, 2012; Turnbull and Turvill, 2012).

Current institutional structure and operation cultures are not congruent with the need for multidimensional approaches for DRM at the national and local level in a number of countries (ISDR et al., 2010; ISDR, 2011). This chapter identified similar institutional barriers in adaptation planning and implementation discussed in Section 15.5.1.2 (Few et al., 2007b; Urwin and Jordan, 2008; Corfee-Morlot et al., 2009; Keskitalo, 2009; Pahl-Wostl, 2009; Measham et al., 2011; Robinson and Berkes, 2011; Sietz et al., 2011; Nilsson et al., 2012; Rodima-Taylor et al., 2012; Glaas and Juhola, 2013). Addressing these institutional barriers in DRM and CCA jointly can help create more efficient and effective strategies and actions to adapt to short-, middle-, and long-term climate impacts. Planning has been highlighted as key tool for DRM and adaptation but it requires also transformations in its operational structure and practices to fulfill this role (Wilson, 2006; Blanco and Alberti, 2009; Roberts, 2010; Preston et al., 2011; Carmin et al., 2012; Mathew et al., 2012; Rodima-Taylor et al., 2012; Sanchez-Rodriguez, 2012).

DRM experiences reveal the importance of linking development and disaster risk prevention and reduction. Strengthening the integration of CCA with development has been also suggested (Lemos et al., 2007; Ewing et al., 2008; Hodson and Marvin, 2009; Hardee and Mutunga, 2010; Sietz et al., 2011). Connecting DRM and CCA to existing development pressures, agendas, policies, governance structures, and communitywelfare can help reduce the risk of unintended consequences of adaptation. DRM would also facilitate the support and acceptance of adaptation by decision makers and stakeholders at the subnational and national level (Dovers, 2009; Sovacool et al., 2012). Integrating DRM and CCA with development strategies, policies, plans, actions, and pressures can help address social vulnerability to climate change while providing opportunities for adaptation.

National and local efforts in disaster risk reduction recognize the importance of considering DRM a continuous learning process. Adaptation to climate change can also be viewed as a continuous learning process (not a single outcome), requiring regular monitoring and evaluation, as climatic and socioeconomic conditions change, and knowledge of the impacts increases (Adger and Barnett, 2009; Hinkel et al., 2009; Hulme et al., 2009; Preston et al., 2009; Arnell, 2010; Hofmann et al., 2011). Considering DRM and CCA learning processes assists in creating integrated approaches for national and local development strategies and plans. The process can also attend to intersecting social processes and help alleviate differing vulnerabilities that result from inequalities in socioeconomic status, income, and exposure to climate risks.

Lessons from DRM highlight the importance of participatory approaches and the use of local knowledge in the design and implementation of disaster risk prevention and reduction and CCA (Few et al., 2007b; van Aalst et al., 2008; ISDR et al., 2010; UNDP, 2010b; EIRD, 2012). By the same token, local knowledge-based adaptation is primarily focused on the use of traditional knowledge to increase adaptive capacity at the community level (see Table 15-1 for examples). Local knowledge often highlights vulnerabilities and impacts that may not be well known owing to the close interactions between climatic and non-climatic stressors associated with structural inequalities to vulnerability in societies (exposure, sensitivity, and adaptive capacity) (Majule et al., 2013). Combining top-down and bottom-up approaches and using low-regret strategies and actions in DRM and in adaptation planning and implementation increase climate resilience, improve livelihoods, reduce development pressures, and strengthen economic and social well-being (Moser and Satterthwaite, 2008; Hallegatte, 2009; Bizikova et al., 2010b; UNDP, 2010b). It can also help alleviate the concerns of limiting the effectiveness of policy interventions, as mentioned in Section 15.2.1.

15.3.3. Adaptation and Development

Discussions of the relationships between sustainable development and climate change have increased over the past decades (Cohen et al., 1998; Yohe et al., 2007; Bizikova et al., 2010a). As impacts of climate change hinder the achievement of development goals at all scales, O'Brien et al. (2012) emphasize that disaster risk management is increasingly considered as one of the frontlines of adaptation, and a promising arena for mainstreaming or integrating climate change adaptation into sustainable development planning. In many cases, the most attractive adaptation actions are also those that offer development benefits in the near term, as well as reductions of vulnerabilities in the longer term (Agrawala, 2005; Klein et al., 2007; McGray et al., 2007; Hallegatte, 2008; NRC, 2010). In developing countries, adaptation has been embedded in the development context in NAPAs and national adaptation strategies.

Attention to the social dimensions of adaptation, including rates of change in social conditions, in part of the literature coincides with the interest of international organization and scholars in the relationship between adaptation planning and implementation and development (UNDP, 2004; Lemos et al., 2007; Dovers, 2009; OECD, 2009; Stringer et al., 2009; Bizikova et al., 2010b; UN-HABITAT, 2011b). The literature supports the standing contention that adaptation takes place as a response not just to climate change but also to multiple stresses (Adger et al., 2005; Thomas and Twyman, 2005). Linking existing policy, agendas, knowledge, risks, and issues communities already face with adaptation planning can help reduce the unintended consequences of adaptation (Dovers, 2009). The importance of climate change adaptation is also influenced by how the issue is framed. For example, to the extent that it is viewed as a public safety issue or a development issue, it may have greater resonance within local government (Measham et al., 2010). Other authors consider integrating local knowledge and experience, including households, into multidimensional and multiscale approaches to guide the construction of adaptation responses to climate change, and integrate them with development strategies (Ewing et al., 2008; Moser and Satterthwaite, 2008; Blanco and Alberti, 2009; Hodson and Marvin, 2009).

Other literatures emphasize the role of planning as a switchboard for adaptation and development (Füssel, 2007; Hallegatte, 2009; Preston et al., 2011). This might require systemic changes to enable planning approaches capable of managing complexity and uncertainty, and multidimensional and multilevel coordination (Pahl-Wostl, 2009; Tompkins et al., 2010; Huntjens et al., 2011, 2012).

15.4. Tools Used for Decision Making, Planning, and Implementation

15.4.1. Decision Support Tools

A feature of adaptation planning is decision making under uncertainty. There is a large body of literature that examines how to integrate uncertain information into decision-making processes and use this information to evaluate the significance of uncertainties for decision outcomes. Treatment of uncertainty is dealt with in Section 2.3.1. Adaptation decision making is informed by various tools present in both top-down and bottom-up forms. Top-down tools often include downscaled simulated climate scenarios for regional level projections, accompanied by expert opinions. These are applied using multi-criteria optimization methods, evaluation of feasibility that may include cost effectiveness such as cost-benefit analyses, and assessment of potential impact severity (Carter et al., 1994; IPCC-TGICA, 2007; Adger et al., 2009a,b; see also Sections 5.5.3, 9.4.2). In the bottom-up approach, those affected or at risk examine their own impacts and vulnerabilities and incorporate adaptive options for the appropriate sector or community. Stakeholders may organize social and institutional activities in the light of actions and interactions among those engaged in the process. Advances in stakeholder participatory methods have significantly enhanced the development of this type of decision-making tool in recent years (Epstein and Axtell, 1996; Wolfram, 2002; Kaner et al., 2007; see also Section 2.4.4).

No single tool suits all circumstances of adaptation decision making, although information development tools such as Community-based Risk Screening Tool-Adaptation and Livelihoods (CRiSTAL) can manage diverse vulnerabilities and risks (IISD, 2012). By outlining the problems and the available inputs to the adaptation decision process, this tool may provide a suitable option (Gimblett, 2002). IPCC (2012) notes there are distinct differences in problem orientation and solution space depending on whether an adaptation plan commences with climate modeling outputs versus that of a risk- and vulnerability-based framework.

15.4.2. Tools for Planning

Uncertainties in climate change, coupled with the complexities of social-ecological systems, require a dynamic approach to adaptation planning and implementation. Knowledge about climate change risks from various stakeholders and organizations is an essential resource for adaptation planning. Multidisciplinary efforts, some of which are discussed below, have engaged in development, assessment, and communication of climate information and risks across different time scales.

15.4.2.1. Monitoring, Modeling, and Spatially Integrated Tools

Integration of monitoring and/or modeling systems with the techniques of GIS can strengthen adaptation planning and implementation. The complex, multiscale, interdisciplinary nature of climate change impacts on socio-ecological systems has made the computer-based modeling approach a tool for understanding the evolving processes and future conditions (Alter, 2004; Pyke et al., 2007). These include remote-sensing and global positioning systems and discussion support or a dynamic dialog between researchers and practitioners. As a result, much more powerful, process-visual, and spatially implicit decision-support systems have been developed. One example is the development of the Invasive Species Forecasting System (ISFS) (Stohlgren et al., 2005) that combines USGS science and NASA Earth observations with software engineering to provide regional-scale patterns of invasive species and vulnerable habitats. Similarly, in the Yellow River, the second largest drainage basin of China, low-flow seasons caused the lower channel to dry up and forced governments to develop a basin-scale decision-support system (Li and Li, 2009). The European Spatial Planning Adapting to Climate Events Project (ESPACE) asserts that urban planning contributes to adaptive efforts by utilizing tools for adaptation through both conventional and green infrastructure and design (porous surfacing, green roofs, etc.) (ESPACE, 2008).

15.4.2.2. Communication Tools

There are a wide range of communication tools that can play an important role in adaptation implementation. These tools include brochures, bulletins, posters, magazines, policy briefs, videos, TV and radio broadcasts, Internet, and many more that are being employed to carry out participatory dialogs. These provide avenues for communication among information developers (e.g., scientists, trainers, project implementers, government agencies, etc.) and community members, groups at risk, etc., who also influence the nature of information disseminated. At the local level, interactive strategies include theater, role-playing, music, learning-by-doing, and hands-on exercises. There are also group discussions of community members to debate climate risks and possible solutions to cope with impacts that positively affect behavior and practices. Reports, concept notes, brochures, magazines, presentations, and workshops provide more effective tools to communicate with policy makers at local and national levels. At the country/regional level, broad dissemination channels such as TV, radio and internet broadcast, blogs, and high-level summits have been effective in creating widespread awareness, as demonstrated in the Advancing Capacity for Climate Change Adaptation (ACCCA) project (http://www.acccaproject.org/accca/), UK Climate Impacts Program (UKCIP; Pringle, 2011), and the SREX report (IPCC, 2012).

To assist the syntheses, a variety of rule- or matrix-based methods have been applied for screening adaptation options such as relative cost effectiveness of alternative adaptation measures (Benioff and Warren, 1996), and for adaptive opportunities for coastal zone management (Uljee et al., 1999). Greater emphasis on user interaction, sensitivity analysis, and capabilities currently provides more effective visualization and customized reports (Sarewitz et al., 2000; Sarewitz, 2004). Multi-criterion and multi-actor participatory approaches allow users to consider alternative adaptation strategies and evaluate trade-offs, typically in the development of tools for environmental assessment and management (Julius and Scheraga, 2000).

15.4.2.3. Early Warning and Information Systems

Monitoring and early warning systems (EWS) have long played important roles in helping in adjustment and adaptation especially on the local

Box 15-1 | Examples of Tools and Measures

Conventional and Green Infrastructure

- Large investment has been made on engineered structure to protect coastal areas against climate-related events. In New York City, infrastructure adaptation strategies to climate change include both hard and soft measures. Hard structures in the New York City region include seawalls, groins, jetties, breakwaters, bulkheads, and piers, but these have not yet been strengthened and elevated over time in response to projected rates of sea level rise (Gornitz, 2001). Storm-surge barriers have been recommended to protect against high water (Aerts et al., 2009; Zimmerman and Faris, 2010). Such barriers are also used in the Thames in London (UK Environment Agency, 2012; see Box 5-1) and Rotterdam (Aerts et al., 2009). Soft measures involve wetland and dune restoration, beach nourishment, enhancement, and expanding the Staten Island Bluebelt—a stormwater management system to other areas (NYCDEP, 2008).
- In the Netherlands, during the second half of the 20th century, large structures had been built to protect the coastal area (Kabat et al., 2009). To keep the country flood-proof over the 21st century, an estimated total cost of implementing a new ambitious plan is €2.5 to 3.1 billion a year to 2050, representing 0.5% of the current Dutch annual gross domestic product (GDP) (Stive et al., 2011). The new plan is a paradigm shift that addresses coastal protection "working with nature" and providing "room for river" instead of only "fighting" the forces of nature with engineered structures.
- Development of engineered structures can lead to more greenhouse gas emissions and potential negative impacts on ecosystems (see Section 5.5.6). On the contrary, green infrastructure (porous surfacing, green roofs, etc.) have been used in parts of Europe (ESPACE, 2008), Portland, Philadelphia, New York (Foster et al., 2011), London (GLA, 2011), and Quy Nhon in Vietnam (Brown et al., 2012) (see Section 8.3.3.7).

Use of Information and Communication Technologies

- Information and communication technologies (ICTs) can help strengthen the physical preparedness of livelihood systems for climate change-related events. These can contribute to design of defenses and determination of their optimal location, and make the livelihood system more robust. GIS technology was applied to foster the ability of the community to deal with climate change hazards and trends in the Philippines (IAPAD, 2010) and form modeling processes of climate change adaptation that supported regional stakeholders to develop better protection of key spaces in the landscape (Bardsley and Sweeney, 2010). Visualization of sea level rise and climate change damage in Delta in British Columbia, Canada, increased awareness of long-term risks and response challenges to local community, government, and the public (Shaw et al., 2009).
- By sharing observations and reflections through ICT tools, users foster new ways of assimilating or translating information, which can be shared through wider networks, and then influence action, enabling new experiments/practices to take place. This generation of new and broader learning cycles will in turn strengthen systematic resilience (Ospina and Heeks, 2010). Karanasios (2011) outlines the range of new and emergent ICTs (e.g., wireless broadband, sensor networks, GIS and Web-based tools) being applied to climate change issues, and investigates their use in developing countries.

Other Tools

- Other tools are being used such as insurance (see Section 8.4.2; Table 10-8), linking CCA to ICZM (Section 5.5.3) or DRR (Section 8.3.2.2), reduction of emissions from deforestation and forest degradation (Section 13.3.1.2), using climate change scenarios (Box 14-1), ecosystem-based adaptation (Box CC-EA, Box 8-2, Section 22.4.5.6, Figure 22-6), and land use (Box 25-10).

scale. The disaster research community has shown that successful warnings of impending events are those that are complemented by information on the risks actually posed by the hazards and by potential strategies and pathways to mitigate damage within a particular context (Drabek, 1999; UNISDR, 2006). The use of climate data analyses and projections in early warning and information systems is an important and established mechanism to inform disaster risk mitigation (Pulwarty and Verdin, 2013) or climate-related health risks (see Section 11.7.3). It helps to ensure the link between generation and application of climate knowledge for management of climate-related risks and CCA. In this

regard, interest in climate services is growing in many countries (see Section 2.4.1).

EWS includes a diversity of approaches. These range from technological advances in systems, satellite information, and climate modeling (UNISDR, 2006; Smith et al., 2009; Bierbaum et al., 2013) to local level early warning based on traditional knowledge needed to develop and inform strategic response options in adaptation planning and implementation. Local knowledge can be complemented with scientific climatic data, research, and planning tools (GIS, modeling, etc.) to strengthen community-based monitoring and vulnerability assessment in disaster risk management and adaptation to climate change (Green and Raygorodetsky, 2010; Kalanda-Joshua et al., 2011; Newsham and Thomas, 2011; Nakashima et al., 2012).

Current science and technology do not resolve the uncertainties in modeling the response of ecosystems to climate change and management interventions at levels needed for probabilistic early warning. Yet the need for precise climate information is often overstated (Smith et al., 2009). The long-standing experience with climate extremes and variability offers many usable lessons in spite of these uncertainties. The impacts of climate change will be most strongly felt by populations vulnerable to changes in the distribution and magnitude of extreme weather and climate events, as these affect crops, disease outbreaks, and soil and water quality. The diverse types of EWS in developed and developing countries are valuable tools that could help societies develop strategies to cope and adapt to climate-related risks.

15.4.3. Technology Development, Transfer, and Diffusion

Development and diffusion of technologies and management practices will continue to be critical to many adaptation efforts. While a wide range of adaptations are possible with current technologies and management practices, technologies expand the range of adaptation possibilities by expanding opportunities or reducing costs (Smith et al., 2009). Technologies related to information collection and diffusion are particularly important for adaptation planning, including technologies for data collection and information dissemination during extreme events and emergencies. Despite remaining uncertainties, technologies to project climate changes, and identify potential impacts and vulnerabilities, are frequently seen as precursors to successful adaptation planning. Developing countries require enhanced access to improved climate models, but also adaptation planning tools that focus on robustness in the face of uncertainty (Dessai et al., 2009).

Technology choices can both reduce and exacerbate risk, and their use in adaptation planning and implementation requires considering their potential effects (Jonkman et al., 2010). For example, technologies can strengthen physical infrastructure, such as bridges and buildings, so that they can withstand more extreme hazards. However, relatively centralized high-technology systems increase efficiency under normal conditions but risk cascading malfunctions in the event of emergencies. In some circumstances, technologies to reduce short-term risk and vulnerability contribute to increased future vulnerability to larger extreme events (Etkin, 1999; Moser, 2010). This was seen in the impacts of Hurricane Katrina on New Orleans, where a flood defense system enabling construction in a floodplain was subject to catastrophic failure in the face of a particularly large extreme event (Freudenburg et al., 2008; Link, 2010).

International efforts for technology transfer have been concentrated in the UNFCCC framework's five themes: technology needs and needs assessments, technology information, enabling environments, capacity building, and mechanisms for technology transfer. A key project is developing a technology transfer clearinghouse called TT:CLEAR, and establishing a Technology Center and Network (UNFCCC, 2012). However, successful technology transfer requires not only exchange of technological solutions, but also strengthening policy and regulatory environments, and capacities to absorb, employ, and improve appropriate technologies. In both developed and developing countries, multilateral institutions can support collaboration that engages private interests in regulatory planning and possibly activities, particularly if ongoing funding is expected (Tessa and Kurukulasuriya, 2010).

15.4.4. Insurance and Social Protection

Insurance is widely seen as a cost-effective tool for adaptation planning and implementation for increasing financial resilience, especially when compared to *ex post* disaster aid (Warner et al., 2009; Linnerooth-Bayer et al., 2011). It is in this context that insurance has received the attention of those planning and managing climate adaptation: IPCC's SREX report (IPCC, 2012) recognizes that risk sharing and transfer mechanisms at local, national, regional, and global scales can increase resilience to climate extremes, while for slow-onset impacts it is usually considered unsuitable (Collier et al., 2009). The main question is if and how insurance products, particularly natural disaster and agricultural cover, can be designed so that they trigger adaptive behavior. The insurance price signal is widely considered as the first step in taking risk reduction measures (Fankhauser et al., 1999), but it does not imply that action will be taken. In fact those at risk, such as local farmers, may not have the capacity to act because they lack tools, methods, or financial means. The role of insurance is also discussed in Section 10.7 in this report.

Many scholars agree on the theoretical potential for insurance to facilitate climate risk reduction through a wide scale of activities, ranging from awareness raising and sharing of modeling and risk mapping data and tools, to providing economic incentives for risk reduction and mandating adaptation as a condition for granting insurance (Crichton, 2008; Suarez and Linnerooth-Bayer, 2011; Surminski and Oramas-Dorta, 2011; Paudel, 2012). Evidence of how this is successfully achieved is limited to private insurance and reinsurance companies, scientists, and governments aiming at adaptation, most notably through sector initiatives such as ClimateWise and UNEPFI's Insurance Working Group (Mills, 2004). Existing insurance schemes for flooding in the USA (Michel-Kerjan and Kunreuther, 2011) and the UK (Ball et al., 2013) show the challenges of fostering risk reduction through insurance. Those two schemes are on opposite ends of a broad scale—the U.S. National Flood Insurance Program being a public sector scheme, while the UK's flood insurance is provided by a private insurance market. Both systems struggle with the implementation of risk-based pricing as the guiding principle of insurance. Picard (2008) highlights the trade-off between effectiveness of risk based pricing and equity—as those most vulnerable struggle to

pay for risk-based premiums. Public-private partnerships may be able to assist through premium subsidies, or broader collaboration on risk management, as seen in the case of the UK's flood insurance.

The use of insurance to manage extreme weather events varies across the world, with penetration of insurance coverage determined mainly by income levels (Ranger and Surminski, 2012), with insurance in most low- and middle-income countries still in its infancy (Churchill, 2007; Warner et al., 2009). Demand-side limitations include access to and affordability of coverage, desirability of products, and financial literacy (Linnerooth-Bayer et al., 2011).

Over the last decade, risk transfer schemes have been developed in low-income countries, often run as pilot projects between the private sector and public authorities. Analysis of the existing disaster risk transfer activities in low- and middle-income countries indicates that the potential for utilizing risk transfer for risk reduction is far from exhausted, with only very few schemes showing an operational link between risk transfer and risk reduction (Surminski and Orama-Dorta, 2011; IPCC, 2012, p. 355). Some innovative efforts are currently being tested to address these challenges—such as the El Niño-Southern Oscillation (ENSO) insurance scheme in Peru, an index-based forecast insurance that pays out on the basis of a seasonal forecast, giving policyholders the opportunity to use the pay-out for preventive measures, such as the purchase of drainage cleaning machinery or to improve transport infrastructure or adjust cash flows in anticipation of possible income reduction (GIZ, 2012). A regional insurance system is also an innovative tool for sharing disaster risks among participating countries. For example, the Caribbean Catastrophic Risk Insurance Facility (CCRIF) was established as a risk pooling facility, attended by 16 countries, to limit the financial impact of catastrophic hurricanes and earthquakes to Caribbean governments by quickly providing short-term liquidity. Another approach is the agricultural insurance scheme in Sudan, where farmers are required to adopt more resilient farming practices to gain access to the risk transfer scheme and the Horn of Africa Risk Transfer for Adaptation (HARITA) scheme in Ethiopia (Oxfam, 2009).

There are various adaptation options that target the specific vulnerability of disadvantaged groups as social options of CCA. Social protection programs include public and private initiatives that transfer income or assets to poor people, protect against livelihood risks, and raise the social status and rights of the marginalized (see Glossary). The roles of social protection in CCA are discussed in Section 14.3.2 and Box 13-2.

15.5. Governance for Adaptation Planning and Implementation

15.5.1. Institutional Dimensions for Planning and Implementing Adaptation

15.5.1.1. Importance of Institutional Dimensions

Since the AR4 findings on substantial barriers to mainstreaming adaptation and suggested research challenges in further understanding adaptation processes of mainstreaming adaptation (Adger et al., 2007), the academic literature identifying drivers and barriers to climate adaptation planning and implementation has increased. A recent review has shown that more than 200 context-dependent barriers have been identified in 81 peer-review papers, mostly but not exclusively based on small-*N* inductive case studies (Biesbroek et al., 2013). The message from the literature is clear: adaptive capacity signals potential but does not guarantee adaptive action (O'Brien et al., 2006; Adger and Barnett, 2009; Burch, 2010; Tompkins et al., 2010). While there is growing recognition that adaptation planning is essential (Ayers and Huq, 2009; Wilbanks and Kates, 2010; Ford et al., 2011), research reporting on planning and implementation has increased appreciation of the magnitude of the institutional dimension for limiting or enabling the mainstreaming of climate adaptation (Moser and Ekstrom, 2010; Berkhout, 2012; Biesbroek et al., 2013). Several studies, in different settings, for example, river basin management in Brazil (Engle and Lemos, 2010), municipalities in Canada (Burch, 2010) and Australia (Measham et al., 2011), villages in Western Nepal (Jones and Boyd, 2011), and pastoralist groups in Kenya (Eriksen and Lind, 2009; Robinson and Berkes, 2011; Adhikari and Taylor, 2012), illustrate such difficulties. Adaptation studies, targeting specifically how institutional dimensions limit or enable the mainstreaming of climate change considerations in policy making, planning, and decision making at different levels and in different sectors, have grown in number (Crabbé and Robin, 2006; Koch et al., 2007; Roberts, 2008; Bulkeley et al., 2009; Engle and Lemos, 2010; Glaas et al., 2010; van den Brink et al., 2011; Storbjörk and Hedrén, 2011; Huntjens et al., 2012; Termeer et al., 2012; Glaas and Juhola, 2013).

Institutions are composed of tangible formal procedures, laws and regulations and tacit informal values, norms, traditions, codes, and conducts that shape expectations and guide actions among actors and organizations, serving as manifestations of institutions (Ostrom, 1990; Dovers and Hezri, 2010). Adaptation planning and implementation follows formal institutions associated with regulations, policies, and standards created and enforced by government actors but also requires the participation of informal institutions through interactions among stakeholders according to cultural, social, and political conditions in societies (Moser and Satterthwaite, 2008; Carmin et al., 2012). Chapter 14 describes the importance of these institutional frameworks for adaptive capacity. Chapter 16 presents a framework for adaptation, opportunities, and limits, where governance and institutional arrangements are included. This section assesses the literature on how institutional dimensions limit or enable adaptation planning and implementation and what lessons can be learned from these experiences.

15.5.1.2. Institutional Barriers

While the literature clearly states that institutional dimensions may both enable and limit adaptation planning and implementation, the literature referred to in Section 15.5.1.1 has so far mostly reported on how current institutional arrangements restrict the mainstreaming of climate adaptation. Biesbroek et al. (2013) have stated that although studies in developed countries are more common and comparative approaches of institutional dimensions, exploring differences and similarities in different countries, are rare, institutional dimensions are highlighted for both developing and developed countries. Low-income developing countries report on weak institutional environments and middle- and high-income countries emphasize institutional barriers that prevent the

mobilization of adaptive capacity. Barriers in general are seen as dynamic and context dependent across sectoral, spatial, and temporal scales, meaning that how a particular institutional barrier operates to either strengthen or limit adaptation planning and implementation can vary both between and within countries, depending on case study locations. Also, the importance and severity of each barrier to the proposed change supposedly changes over time and interacts with other constraints (Burch, 2010; Moser and Ekstrom, 2010; Biesbroek et al., 2013). Barriers are also shown to differ in different stages of planning and implementation, for example, initial problem framing and agenda setting, planning and strategy-making, implementation, monitoring, and evaluating, which studies have increasingly made clear (Moser and Ekstrom, 2010; Dannevig et al., 2012; Mees et al., 2012). The following paragraphs illustrate five of the most commonly emphasized barriers or enablers of institutional change.

First, the importance of multilevel institutional coordination between different political and administrative levels in society is increasingly cited in both developing and developed countries as challenging (Few et al., 2007a; Urwin and Jordan, 2008; Corfee-Morlot et al., 2009; Keskitalo, 2009; Pahl-Wostl, 2009; Measham et al., 2011; Robinson and Berkes, 2011; Sietz et al., 2011; Nilsson et al., 2012; Rodima-Taylor et al., 2012; Glaas and Juhola, 2013). Several studies report on unclear roles and responsibilities between levels and actors inhibiting climate adaptation. They show that there are few national requirements or guidelines to help local governments approach climate adaptation, stressing the importance of developing regulations, policies, and codes to support the institutionalization of local climate actions (Næss et al., 2005; Crabbé and Robin, 2006; Storbjörk, 2007; Glaas et al., 2010; Mozumder et al., 2011; Adhikari and Taylor, 2012; Carmin et al., 2012; Hedensted Lund et al., 2012; Peach Brown et al., 2013). Vammen Larsen et al. (2012) stress that climate change does not possess clear institutional characteristics as a municipal professional area. Rather, it is viewed as a void with no clear rules and norms according to which politics are to be conducted and policy measures agreed on. This has meant that climate adaptation remains ad hoc and based on processes of "muddling through" in a sense that increases risks of failure (Preston et al., 2011).

Further, the literature shows that the lack of clear national agendas and incentives may burden local governments differently, based on their different capacities (Anguelovski and Carmin, 2011; Juhola and Westerhoff, 2011; Dannevig et al., 2012). Authors have also cautioned against a too heavy emphasis on national guidance, suggesting that centralized approaches may in some cases constrain local initiatives and create unfortunate dependencies. Instead a combination of top-down and bottom-up activities is proposed where national actors set a proactive agenda for climate adaptation and support implementation that occurs at subnational levels (Urwin and Jordan, 2008; Bulkeley et al., 2009; Preston et al., 2013). Connected to this question of guidance and support is also a large strand of research showing that simply producing more and better knowledge is not sufficient. This illustrates the role of knowledge-brokers, policy entrepreneurs, and bridging organizations to communicate and mediate the co-production of knowledge between science and practice and make climate knowledge consistent and credible at the appropriate decision-making scale (Tribbia and Moser, 2008; Amundsen et al., 2010; Tompkins et al., 2010; Mozumder et al., 2011).

Second, the literature show that key actors, advocates, and champions are decisive for initiating, mainstreaming, and sustaining momentum for climate adaptation planning and implementation in different national settings (Bulkeley et al., 2009; Burch, 2010; Moser and Ekstrom, 2010; Tompkins et al., 2010; Garrelts and Lange, 2011; Runhaar et al., 2012; Romero-Lankao, 2012). Key actors can be particularly important in the absence of strong national level policies and strategies (Anguelovski and Carmin, 2011; Dannevig et al., 2012). Champions further involve actors in different roles, from junior staff to senior executives and elected representatives (Measham et al., 2011). The literature on leadership has distinguished between different types of leadership, where visionary leadership means showing direction and motivating others; entrepreneurial leadership means ability to get things done; and, finally, collaborative leadership means bridging gaps, spanning boundaries, and building coalitions (Gupta et al., 2010; van den Brink et al., 2011). Although there is wide agreement that leaders are key for driving change, a dependency on personal commitments and dedication of key individuals may render adaptation planning and implementation fragile if it takes place at the price of organizational learning (Næss et al., 2005; Crabbé and Robin, 2006; Storbjörk, 2010).

Third, the horizontal interplay between actors and policies operating at similar administrative levels is seen as key in institutionalizing climate adaptation. Several international studies have shown that local governments and administrations consist of different professional silos with their own internal norms, values, and priorities and that the institutional rigidity of existing administrative and political sectors creates unfortunate compartmentalization where climate adaptation is seen as the isolated task of a singular sector that may hinder mainstreaming and horizontal coordination across sectors and departments (Mickwitz et al., 2009; Burch, 2010; Roberts, 2010; Storbjörk, 2010; Runhaar et al., 2012; Vammen Larsen et al., 2012; van den Berg and Coenen, 2012; Wilby and Keenan, 2012). Preston et al. (2011) have determined that adaptation plans from Australia, the UK, and the USA largely frame adaptation in a narrow sense overlooking the capacity and institutional challenges involved in the process of mainstreaming in other sectors. Institutional rigidity also takes the form of path dependency where past policies, decisions, habits, and traditions constrain the extent to which systems can learn or adapt to climate change (Garrelts and Lange, 2011; Berkhout, 2012; Runhaar et al., 2012; Preston et al., 2013). Some authors have identified such cultures of reactive management or structural engineered approaches to climate adaptation negatively influencing institutional change (Næss et al., 2005; Harries and Penning-Rowsell, 2011; Measham et al., 2011). Several writers have emphasized the need to facilitate improved cross-sectoral interaction, exchange, and organizational learning to drive institutional change (Berkhout et al., 2006; Crabbé and Robin, 2006; Pelling et al., 2008; Hinkel et al., 2009; Burch, 2010). How cross-sectoral coordination is achieved in practice remains one of the major challenges in transitioning from planning to implementation.

Fourth, the need to acknowledge political dimensions in planning and implementation is highlighted in several studies, both in developing and developed countries. Studies indicate that politicians have not recognized climate adaptation as being politically urgent enough to elevate on the policy agenda. Subsequently they identify a tendency to prioritize other political concerns, often more short-term tangible issues (O'Brien et al.,

2006; Storbjörk, 2007; Glaas et al., 2010; Corfee-Morlot et al., 2011; Measham et al., 2011; Runhaar et al., 2012; Preston et al., 2013). This has implications for the availability of resources and financial means in the form of staff and time (Tribbia and Moser, 2008). Other studies document competing values, conflicting objectives, tensions, and trade-offs between different policy agendas and priorities in planning and implementing climate adaptation (Næss et al., 2005; Berkhout et al., 2006; Adger et al., 2009a; O'Brien and Wolf, 2010; Measham et al., 2011; Storbjörk and Hedrén, 2011). In a developing country context, a study in the drylands of Kenya calls for increased consideration of political dimensions of local adaptation by showing how power relations at multiple geographic scales and interaction of informal institutions, for example, clans and spiritual leaders and government institutions, shape the local negotiation of conflicting interests (Eriksen and Lind, 2009).

Fifth, improved coordination between formal governmental and administrative agencies and private stakeholders is highlighted in the literature. Private sector involvement is often seen as a way to increase the efficiency of climate adaptation (Engle and Lemos, 2010; Mees et al., 2012; Tompkins and Eakin, 2012). As part of highlighting private sector involvement, studies from developing and developed countries emphasize the need for stakeholder participation, representation, accountability, and equality to influence the sharing and shaping of knowledge in adaptation decision making and achieve change on the ground (Gupta et al., 2010; Harries and Penning-Rowsell, 2011; Robinson and Berkes, 2011; Adhikari and Taylor, 2012; Huntjens et al., 2012; McNeeley, 2012; Tompkins and Eakin, 2012). Participatory approaches potentially allow maintaining regard for the highly localized and contextual nature of climate adaptation, balance standardization and context in adaptation planning and implementation, and bolster support for and facilitate implementation (Preston et al., 2011; Mees et al., 2012). Elaborate forms of participatory designs for facilitating a co-production of knowledge, interactive learning, and stakeholder exchange, mediated by boundary organizations and knowledge brokers, are being undertaken but more are needed (Pahl-Wostl, 2009; Pulwarty et al., 2009; Tompkins et al., 2010; Jonsson et al., 2012). At the same time authors clarify that stakeholders can hold private, sectarian interest and represent local elites, meaning that which voices actually get represented is an important issue (Romero-Lankao, 2012). Studies in western Nepal have documented obstacles to political inclusion due to social status and caste-based political discrimination where societal elites suppress marginal voices (Jones and Boyd, 2011). Other studies have documented how existing centralized top-down institutions have been complemented and sometimes challenged by public-private partnerships at critical stages in implementation (Juhola and Westerhoff, 2011; Rodima-Taylor et al., 2012).

15.5.1.3. Facilitating More Effective Climate Adaptation Planning and Implementation

Although Section 15.2 shows that international studies clearly report a large number of ongoing responses to support climate adaptation, which are most commonly incremental responses within existing institutional arrangements (with some rare examples of institutional transformations), there is a large body of evidence of the mainstreaming of climate adaptation resulting in limited implementation. Subsequently most studies on climate adaptation planning and implementation have focused on identifying barriers and challenges. Biesbroek et al. (2013) have suggested moving forward in our current context-specific and fragmented understanding of barriers, including institutional dimensions, and embrace comparative approaches, synthesizing knowledge and analyzing barriers more systematically. Recent discussions suggest focusing more attention on how to transform barriers to enablers of action and institutional change (Burch et al., 2010; Moser and Ekstrom, 2010; Park et al., 2012; Biesbroek et al., 2013). Dovers and Hezri (2010) have claimed that there is a predominant focus in adaptation research on what should happen rather than how that might be achieved, the latter targeting strengths and weaknesses with different forms of institutional structures, procedures, and ways of organizing climate adaptation that supports change. Others have suggested that monitoring and evaluating the effectiveness of strategies adopted and interventions undertaken needs further attention (Mullan et al., 2013). Further, it is suggested that propositions for change tend to be driven by theory rather than empirically substantiated and tested and that the adaptation literature would benefit by embracing lessons and experiences of mechanisms for enabling institutional change gained in other policy sectors and past policy interventions (Dovers and Hezri, 2010; Biesbroek et al., 2013).

15.5.2. Increasing Capabilities

Governance of adaptation creates the space and conditions for achieving specific goals or collective outputs by aligning principles and norms for regulations, decision-making procedures, and organizations in providing an overarching system to address a challenge comprehensively (Biermann et al., 2009; Young, 2010; DeWulf et al., 2011). However, the embryonic stage of adaptation planning and implementation faces challenges to develop governance approaches (Glaas et al., 2010; Gupta et al., 2010; Tompkins et al., 2010; Carmin et al., 2012; Huntjens et al., 2012; Rodima-Taylor et al., 2012; Mukheibir et al., 2013). The previous section on the institutional dimensions of adaptation in this chapter stressed the obstacles in current structures of national, subnational, and local governments to address complex and multidimensional problems (Wilson, 2006; Koch et al., 2007; Roberts, 2008; Bulkeley et al., 2009; Inderberg and Eikeland, 2009; Engle and Lemos, 2010; Glaas et al., 2010; Sietz et al., 2011; Storbjörk and Hedrén, 2011; van den Brink et al., 2011; Huntjens et al., 2012; Rodima-Taylor et al., 2012; Termeer et al., 2012; Vammen Larsen et al., 2012; Glaas and Juhola, 2013). Similar fragmented approaches for adaptation planning and implementation also hinder a dynamic and diverse participation of other stakeholders in these processes (Folke et al., 2005; Raschky, 2008; Urwin and Jordan, 2008; Coles and Scott, 2009; Dessai et al., 2009; Handmer, 2009; Scheffer, 2009; Nath and Behera, 2010; Reid et al., 2010; Sissoko et al., 2011). In addition, there have been very few documented changes in forecasts, plans, design criteria, investment decisions, budgets, or staffing patterns in response to climate risks (Repetto, 2008; Tompkins et al., 2010; Berrang-Ford et al., 2011).

Expanding and improving capabilities of stakeholders strengthen operational approaches for adaptation to climate change at different levels. The literature recognizes four areas where improved capabilities can facilitate this creation of governance approaches for adaptation

planning and implementation: creating learning processes incorporating various knowledge systems and experiences to facilitate developing a common understanding and policies critical for cross-institutional coordination and multi-stakeholder actions (Engle and Lemos, 2010; Huntjens et al., 2012); enhancing monitoring and evaluation of adaptation planning and implementation currently limiting opportunities for learning and improvement of current and future adaptation initiatives (Manuel-Navarrete et al., 2009; Preston et al., 2011; Nilsson et al., 2012); improving cross-level coordination within government structures at the national, subnational, and local levels (Urwin and Jordan, 2008; Bulkeley et al., 2009; Amundsen et al., 2010; Robinson and Berkes, 2011; Preston et al., 2013); and enhancing the participation of stakeholders from the assessment of vulnerability to the design and implementation of operational approaches of adaptation (Moser and Satterthwaite, 2008; Anguelovski and Carmin, 2011; Carmin et al., 2012; Dannevig et al., 2012).

These interacting aspects strengthen incorporating climate change risks to systems and sectors, and the corresponding response planning and implementation actions occurring at different spatial and temporal scales. They help improve mechanisms to foster and strengthen coordination in the scale of governance together with a clear division of tasks and responsibilities of actors, especially under conflicting time scales of interventions (Koch et al., 2007; Amundsen et al., 2010; Biesbroek et al., 2010, 2011). They can also support addressing jurisdictional scales and mandates across sectors, and local, national, and subnational policies, constricting the potential benefits of close dependencies between institutions, institutional systems, and organizational units in planning and implementation of adaptation (Dovers and Hezri, 2010).

Creating capabilities through coordination is reported to expand the adaptive capacity of local actors and enhance opportunities for policy formulations of larger governance networks and learning opportunities for policy formulations (Keskitalo and Kulyasova, 2009; Owen, 2010). Capturing various perspectives of multiple stakeholders and actors holding different views, power, and influence is pivotal in mutually achieving short-term and long-term adaptation needs to climate change (O'Brien et al., 2008; Shaw et al., 2009; Bardsley and Sweeney, 2010; IAPAD, 2010; Corfee-Morlot et al., 2011). Capabilities to enhance and complement the value of local knowledge through scientific knowledge can become a useful source of community-based adaptation planning and implementation (McLeman et al., 2008; Green and Raygorodetsky, 2010; Berrang-Ford et al., 2011; Birkmann, 2011; Ford et al., 2011; Newsham and Thomas, 2011; Nakashima et al., 2012).

Increasing capabilities for adaptation planning and implementation can also benefit from approaches with greater emphasis on nature-based protection strategies or buffers. Related climate change adaptation efforts also improve ecosystem resilience by implementing sustainable forestry management, expanding floodplain setbacks, implementing coastal afforestation and coral reef propagation, restoring degraded lands, maintaining healthy vegetation on slopes, incentivizing development away from coastal areas and bluffs, and removing barriers to the migration of plants and animals, all of which are necessary for the resilience of communities facing climate change impacts (Tobey et al., 2010; Sovacool et al., 2012).

15.6. Research Needs for Maximizing Opportunities

The following interrelated research needs extracted from the chapter can create and maximize opportunities for adaptation planning and implementation.

The emphasis on impacts and defensive infrastructure has been documented in a number of early adaptation plans (Few et al., 2007a; Hofstede, 2008; Mitchell et al., 2010; Garrelts and Lange, 2011; Harries and Penning-Rowsell, 2011; Rosenzweig et al., 2011; Rumbach and Kudva, 2011; Etkin et al., 2012; IPCC, 2012). Research on the design and implementation of these plans and the lessons that can be extracted from them can help address concerns in the literature that an impact approach can overshadow the analysis of underlying stressors of hazards, the drivers of vulnerability, and opportunities for connecting development pressures and climate change (Lemos et al., 2007; Sabates-Wheeler et al., 2008; Boyd and Juhola, 2009; Hulme et al., 2009; Orlove, 2009; Hardee and Mutunga, 2010; Ribot, 2010; Rumbach and Kudva, 2011; Sietz et al., 2011). These lessons can help balance the design of adaptation planning including projects for defensive infrastructures needed through flexibility and safety margins and at the same time incorporating other actions seeking to reduce social vulnerability and enhancing adaptation. Relevant in these efforts is building a better understanding of how early adaptation plans can transcend from defensive but fragmented approaches to multidimensional policy process recognizing adaptation planning and its implementation as learning processes (Hulme et al., 2009; Biesbroek et al., 2011).

Research on operational strategies and approaches for adaptation can help maximize available resources for adaptation to climate change. Current contributions in the literature help build a better understanding on diverse dimensions of this complex process, but these contributions have provided little attention to the discussion and suggestion of guidelines to build operational approaches. Some authors stress that few studies show how adaptation to climate change is actually being delivered (Arnell, 2010; Tompkins et al., 2010; National Research Council, 2011). Key elements in these research efforts are: expanding knowledge of the connections between adaptation and development in different contexts and at different governance levels (Boyd and Juhola, 2009; Dovers, 2009; Hulme et al., 2009); the role of multiple stresses (not just climate) in adaptation planning and its implementation (IPCC, 2007; Tompkins et al., 2010); and the role of low-regret strategies strengthening operational approaches for adaptation (Hallegatte, 2009; UNDP, 2010a).

Section 15.5.1 highlights how limitations of current institutional arrangements restrict the mainstreaming of climate adaptation (Roberts, 2008; Burch, 2010; Dovers and Hezri, 2010; Engle and Lemos, 2010; Glaas et al., 2010; Moser and Ekstrom, 2010; Jones and Boyd, 2011; Robinson and Berkes, 2011; Storbjörk and Hedrén, 2011; Dannevig et al., 2012; Huntjens et al., 2012; McNeeley, 2012; Vammen Larsen et al., 2012; Biesbroek et al., 2013; Glaas and Juhola, 2013). Expanding research on institutional arrangements in at least three key areas can help improve the implementation of adaptation plans in both developed and developing countries: (1) on approaches to improve multilevel institutional coordination between different political and administrative

levels in society, with a particular emphasis on balancing a combination of top-down and bottom-up activities (Urwin and Jordan, 2008; Bulkeley et al., 2009; Amundsen et al., 2010; Robinson and Berkes, 2011; Preston et al., 2013); (2) on approaches to overcome the institutional rigidity limiting the horizontal interplay within local governments, where climate adaptation is seen as the isolated task of a singular sector, which hinders the mainstreaming and horizontal coordination across professional sectors and departments and constrains the extent to which systems can learn or adapt to climate change (Bulkeley et al., 2009; Burch, 2010; Dovers and Hezri, 2010; Glaas et al., 2010; Storbjörk, 2010; Juhola and Westerhoff, 2011; Hedensted Lund et al., 2012; Runhaar et al., 2012; Uittenbroek et al., 2012; van den Berg and Coenen, 2012; Wilby and Keenan, 2012); and (3) on approaches improving coordination between formal governmental and administrative agencies and social and private stakeholders in order to create participatory approaches maintaining regard for the highly localized and contextual nature of climate adaptation, and facilitating a collaboration for production of knowledge and interactive learning (Pahl-Wostl, 2009; Engle and Lemos, 2010; Tompkins et al., 2010; Preston et al., 2011; Jonsson et al., 2012; Mees et al., 2012).

The literature illustrates a trend to consider planning a problem-free process capable of delivering positive outcomes for adaptation to climate change. Expanding research seeking to build a better understanding of the limitations and strengths of planning can help avoid underestimating the complexity of adaptation as a social process, and creating unrealistic expectations in societies about the capacity of planning to deliver the intended outcome of adaptation (Repetto, 2008; Biesbroek et al., 2009; Blanco and Alberti, 2009; Dovers, 2009; Berrang-Ford et al., 2011; Juhola and Westerhoff, 2011; Mozumder et al., 2011; Preston et al., 2011; Sanchez-Rodriguez, 2012).

Research efforts considering adaptation planning and implementation as learning processes can help in carrying out periodical adjustments to accommodate changes in climate, socioeconomic conditions, and emergent risks in order to strengthen the role of planning as a societal tool for adaptation (Holden, 2008; Frommer, 2009; Hinkel et al., 2009; Glaas et al., 2010; Hofmann et al., 2011). The literature recognizes monitoring and evaluation as important learning tools in adaptation planning but it also acknowledges both as an under-researched topic (Adger et al., 2009b; Preston et al., 2009; Tompkins et al., 2010; Wolf et al., 2010).

Expanding the research on the metrics to characterize the success of the goals of adaptation, the trade-offs involved, and recognizing the importance of context can help avoid generalized assessments about the contribution of adaptation to managing the risks posed by climate change, and to identify what builds adaptive capacity and what functions as limits and barriers to adaptation (Arnell, 2010; Barnett and Campbell, 2010; Engle, 2011).

Adaptation planning and implementation can benefit from holistic approaches afforded by linking adaptation to development; by coupling adaptive improvements in infrastructure with ecosystem services, governance, and community welfare; by improving community resilience through enhancing local ownership; and by creating organizations able to respond to climate change issues through increased adaptive capacity.

References

Abbas, K.J., T.W. Miner, and Z. Stanton-Geddes (eds.), 2012: *Building Urban Resilience: Principles, Tools and Practice*. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 180 pp.

ActionAid, CARE, and WWF, 2012: *Tackling the Limits to Adaptation: An International Framework to Address 'Loss and Damage' from Climate Change Impacts*. ActionAid International, Johannesburg, South Africa, CARE International, Geneva, Switzerland, and WWF, Gland, Switzerland, 31 pp.

Adger, W.N. and J. Barnett, 2009: Four reasons for concern about adaptation to climate change. *Environment and Planning A*, **41(12)**, 2800-2805.

Adger, W.N., N.W. Arnell, and E.L. Tompkins, 2005: Successful adaptation to climate change across scales. *Global Environmental Change*, **15(2)**, 77-86.

Adger, W.N., S. Agrawala, M.M.Q. Mirza, C. Conde, K. O'Brien, J. Pulhin, R. Pulwarty, B. Smit, and K. Takahashi, 2007: Assessment of adaptation practices, options, constraints and capacity. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 717-743.

Adger, W.N., S. Dessai, M. Goulden, M. Hulme, I. Lorenzoni, D.R. Nelson, L.O. Naess, J. Wolf, and A. Wreford, 2009a: Are there social limits to adaptation to climate change? *Climatic Change*, **93(3-4)**, 335-354.

Adger, W.N., S. Dessai, I. Lorenzoni, and K. O'Brien, (eds.), 2009b: *Adapting to Climate Change: Thresholds, Values, Governance*. Cambridge University Press, Cambridge, UK and New York, NY, USA, 532 pp.

Adhikari, B. and K. Taylor, 2012: Vulnerability and adaptation to climate change: a review of local actions and national policy response. *Climate and Development*, **4(1)**, 54-65.

Aerts, J., D.C. Major, M. Bowman, P. Dircke, and M.A. Marfai, 2009: *Connecting Delta Cities: Coastal Cities, Flood Risk Management and Adaptation to Climate Change*. VU University Press, Amsterdam, Netherlands, 48 pp.

Agrawal, A., 2008: *The Role of Local Institutions in Adaptation to Climate Change*. Paper prepared for the Social Dimensions of Climate Change, Social Development Department, The World Bank, Washington, DC, USA, 65 pp.

Agrawal, A., 2010: Local institutions and adaptation to climate change. In: *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World* [Mearns, R. and A. Norton (eds.)]. The World Bank, Washington, DC, USA, pp. 173-198.

Agrawal, A. and N. Perrin, 2008: *Climate Adaptation, Local Institutions, and Rural Development*. IFRI Working Paper No. W081-6, International Forestry Resources and Institutions Program (IFRI), School of Natural Resources and Environment, University of Michigan, MI, USA, 17 pp.

Agrawala, S. (ed.), 2005: *Bridge Over Troubled Waters: Linking Climate Change and Development*. Organization for Economic Co-operation and Development (OECD), Paris, France, 153 pp.

Alam, M., C. Siwar, B. Talib, M. Mokhtar, and M. Toriman, 2011: Climate change adaptation policy in Malaysia: issues for agricultural sector. *African Journal of Agricultural Research*, **7(9)**, 1368-1373.

Alter, S., 2004: A work system view of DSS in its fourth decade. *Decision Support Systems*, **38**, 319-327.

Amundsen, H., F. Berglund, and H. Westskog, 2010: Overcoming barriers to climate change adaptation: a question of multilevel governance? *Environment and Planning C: Governance and Policy*, **28(2)**, 276-289.

Anguelovski, I. and J. Carmin, 2011: Something borrowed, everything new: innovation and institutionalization in urban climate governance. *Current Opinion in Environmental Sustainability*, **3(3)**, 169-175.

Arnell, N., 2010: Adapting to climate change: an evolving research agenda. *Climatic Change*, **100**, 107-111.

Arnell, N.W., 2011: Incorporating climate change into water resources planning in England and Wales. *Journal of the American Water Resources Association*, **47(3)**, 541-549.

Ayers, J. and S. Huq, 2009: Supporting adaptation to climate change: what role for official development assistance? *Development Policy Review*, **27(6)**, 675-692.

Ball, T., A. Werritty, and A. Geddes, 2013: Insurance and sustainability in flood-risk management: the UK in a transitional state. *Area*, **45(3)**, 266-272.

Bardsley, D.K. and S. M. Sweeney, 2010: Guiding climate change adaptation within vulnerable natural resource management systems. *Environmental Management*, **45**, 1127-1141.

Barnett, J. and J. Campbell, 2010: *Climate Change and Small Island States: Power, Knowledge and the South Pacific*. Earthscan, London, UK and Washington, DC, USA, 218 pp.

Barsugli, J., J. Vogel, L. Kaatz, J. Smith, M. Waage, and C. Anderson, 2012: Two faces of uncertainty: climate science and water utility planning methods. *Journal of Water Resources Planning and Management*, **138(5)**, 389-395.

Battiste, M., 2008: Research ethics for protecting indigenous knowledge and heritage: institutional and researcher responsibilities. In: *Handbook of Critical and Indigenous Methodologies* [Denzin, N.K., Y.S. Lincoln, and L.T. Smith (eds.)]. SAGE Publications, Thousand Oaks, CA, USA, pp. 497-510.

Benioff, R. and J. Warren, 1996: *Steps in Preparing Climate Change Action Plans: A Handbook*. U.S. Country Studies Program, Washington, DC, USA, 317 pp.

Berkhout, F., 2012: Adaptation to climate change by organizations. *WIREs Climate Change*, **3(1)**, 91-106.

Berkhout, F., J. Hertin, and D.M. Gann, 2006: Learning to adapt: organisational adaptation to climate change impacts. *Climatic Change*, **78**, 135-156.

Berrang-Ford, L., J. Ford, and J. Patterson, 2011: Are we adapting to climate change? *Global Environmental Change*, **21(1)**, 25-33.

Biermann, F., P. Pattberg, H. van Asselt, and F. Zelli, 2009: The fragmentation of global governance architecture: a framework analysis. *Global Environmental Politics*, **9(4)**, 14-40.

Bierbaum, R., J. Smith, A. Lee, M. Blair, L. Carter, S. Chapin III, P. Fleming, S. Ruffo, S. McNeeley, M. Stults, E. Wasley, and L. Verduzco, 2013: A comprehensive review of climate adaptation in the United States: more than before, but less than needed. *Journal of Mitigation and Adaptation Strategies for Global Change*, **18(3)**, 361-406.

Biesbroek, G.R., R.J. Swart, G.M. Wim, and W. van der Knaap, 2009: The mitigation-adaptation dichotomy and the role of spatial planning. *Habitat International* **33(3)**, 230-237.

Biesbroek, G.R., R.J. Swart, T.R. Carter, C. Cowan, T. Henrichs, H. Mela, M.D. Morecroft, and D. Rey, 2010: Europe adapts to climate change: comparing national strategies. *Global Environmental Change*, **20(3)**, 440-450.

Biesbroek, R., J. Klostermann, C. Termeer, and P. Kabat, 2011: Barriers to climate change adaptation in the Netherlands. *Climate Law*, **2(2)**, 181-199.

Biesbroek, G.R., J.E.M. Klostermann, C.J.A.M. Termeer, and P. Kabat, 2013: On the nature of barriers to climate change adaptation. *Regional Environmental Change*, **13**, 1119-1129.

Birkmann, J., 2011: First- and second-order adaptation to natural hazards and extreme events in the context of climate change. *Natural Hazards*, **58(2)**, 811-840.

Birkmann, J. and K. von Teichman, 2010: Integrating disaster risk reduction and climate change adaptation: key challenges—scales, knowledge, and norms. *Sustainability Science*, **5(2)**, 171-184.

Bizikova, L., S. Burch, S. Cohen, and J. Robinson, 2010a: Linking sustainable development with climate change adaptation and mitigation. In: *Climate Change, Ethics and Human Security* [O'Brien, K., A. St. Clair, and B. Kristoffersen (eds.)]. Cambridge University Press, Cambridge, UK, pp. 157-179.

Bizikova, L., S. Boardley, and S. Mead, 2010b: *Participatory Scenario Development Approaches for Identifying Pro-Poor Adaptation Options*. Discussion Paper No. 18, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 67 pp.

Blanco, H. and M. Alberti, 2009: Chapter 2: Building capacity to adapt to climate change through planning. In: Hot, congested, crowded and diverse: emerging research agendas in planning. *Progress in Planning*, **71(4)**, 158-169.

Boyd, E. and S. Juhola, 2009: Stepping up to the climate change: opportunities in re-conceptualising development futures. *Journal of International Development* **21(6)**, 792-804.

Braman, L., P. Suarez, and M. van Aalst, 2010: Climate change adaptation: integrating climate science into humanitarian work. *International Review of the Red Cross*, **92(879)**, 693-712.

Brekke, L.D., J.E. Kiang, J.R. Olsen, R.S. Pulwarty, D.A. Raff, D.P. Turnipseed, R.S. Webb, and K.D. White, 2009: *Climate Change and Water Resources Management: A Federal Perspective*. USGS Circular 1331, U.S. Department of the Interior, U.S. Geological Survey (USGS), Reston, VA, USA, 65 pp.

Brown, A., A. Dayal, and C.R. del Rio, 2012: From practice to theory: emerging lessons from Asia for building urban climate change resilience. *Environment and Urbanization*, **24(2)**, 531-556.

Buchner, B., A. Falconer, M. Herve-Mignucci, C. Trabacchi, and M. Brinkman, 2011: *The Landscape of Climate Finance*. Report by Climate Policy Initiative (CPI), Venice, Italy, 101 pp.

Bulkeley, H., H. Schroeder, K. Janda, J. Zhao, A. Armstrong, S.Y. Chu, and S. Ghosh, 2009: *Cities and Climate Change: The Role of Institutions, Governance and Urban Planning*. Report prepared for the World Bank Fifth Urban Research Symposium 2009: "Cities and Climate Change: Responding to an Urgent Agenda," Marseille, France, Palais du Pharo, June 28-30, 2009, 92 pp., siteresources.worldbank.org/INTURBANDEVELOPMENT/Resources/336387-1256566800920/6505269-1268260567624/Bulkeley.pdf.

Burch, S., 2010: Transforming barriers into enablers of action on climate change: insights from three municipal case studies in British Columbia, Canada. *Global Environmental Change*, **20**, 287-297.

Burton, I., E. Malone, S. Huq, B. Lim, and E. Spanger-Siegfried, 2005: *Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies and Measures*. United Nations Development Programme (UNDP), Cambridge University Press, Cambridge, UK, 258 pp.

Carmin, J., I. Anguelovski, and D. Roberts, 2012: Urban climate adaptation in the global south: planning in an emerging policy domain. *Journal of Planning Education and Research*, **32(1)**, 18-32.

Carter, T.R., M.L. Parry, H. Harasawa, and S. Nishioka (eds.), 1994: *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations*. CGER-I015-'94, Climate Change Impacts and Adaptations, Intergovernmental Panel on Climate Change (ICCC), World Meteorological Organization (WMO)/United Nations Environment Programme (UNEP), Published by the Department of Geography, University College London, London, UK and the Centre for Global Environment Research, National Institute for Environmental Studies, Tsukuba, Japan, 59 pp.

Chang'a, L.B., P.Z. Yanda, and J. Ngana, 2010: Indigenous knowledge in seasonal rainfall prediction in Tanzania: a case of the South-western Highland of Tanzania. *Journal of Geography and Regional Planning*, **3(4)**, 66-72.

Christiansen, L., A. Ray, J. Smith, and E. Haites, 2012: *Accessing International Funding for Climate Change Adaptation: A Guidebook for Developing Countries*. TNA Guidebook Series, The Technology Needs Assessment (TNA) Project implemented by the United Nations Environment Programme (UNEP) and the UNEP Risø Centre (URC) on Energy, Climate and Sustainable Development and funded by the Global Environment Facility (GEF), UNEP RISØ Centre, Roskilde, Denmark, 65 pp., www.seachangecop.org/sites/default/files/documents/2012%2008%20UNEP%20TNA%20Guidebook_AdaptationFinancing.pdf.

Churchill, C., 2007: Insuring the low-income market: challenges and solutions for commercial insurers. *The Geneva Papers*, **32(3)**, 401-412.

CIF, 2012: *Creating the Climate for Change*. CIF Annual Report 2012, Climate Investment Funds (CIF), The World Bank Group, Washington, DC, USA, 71 pp., www.climateinvestmentfunds.org/cif/sites/climateinvestmentfunds.org/files/2012_Annual_Report.pdf.

City of New York, 2011: *PlaNYC*. Update, 2011, The City of New York, Mayor Michael R. Bloomberg, New York, NY, USA, 199 pp., www.nyc.gov/html/planyc2030/html/theplan/the-plan.shtml.

City of Rotterdam, 2011: *The Rotterdam Programme on Sustainability and Climate Change 2010-2014: Investing in Sustainable Growth*. 2011 Rotterdam Sustainability Monitor, Rotterdam Climate Initiative (RCI), an initiative of the City of Rotterdam, the Port of Rotterdam, the DCMR Environmental Protection Agency Rijnmond and Port and industries' association Deltalinqs of the Rotterdam port and industrial sector, Rotterdam Office for Sustainability and Climate Changes, City of Rotterdam, Netherlands, 59 pp.

Cohen, S., D. Demeritt, J. Robinson, and D. Rothman, 1998: Climate change and sustainable development: towards dialogue. *Global Environmental Change*, **8(4)**, 341-371.

Coles, A.R. and C.A. Scott, 2009: Vulnerability and adaptation to climate change and variability in semi-arid rural southeastern Arizona, USA. *Natural Resources Forum*, **33(4)**, 297-309.

Collier, B., J.R. Skees, and B.J. Barnett, 2009: Weather index insurance and climate change: opportunities and challenges in lower income countries. *The Geneva Papers*, **34**, 401-424.

Corfee-Morlot, J., L. Kamal-Chaoui, M. Donovan, I. Cochran, A. Robert, and P.J. Teasdale, 2009: *Cities, Climate Change and Multilevel Governance*. OECD Environmental Working Papers No. 14, Organisation for Economic Co-operation and Development (OECD), OECD Publishing, Paris, France, 123 pp.

Corfee-Morlot, J., I. Cochran, S. Hallegatte, and P.J. Teasdale, 2011. Multilevel risk governance and urban adaptation policy. *Climatic Change*, **104**, 169-197.

Corfee, J., J. Parzen, M. Wagstaff, and R. Lewis, 2010: Preparing for climate change: the Chicago Climate Action Plan's adaptation strategy. *Journal of Great Lakes Research*, **36(2)**, 115-117.

Crabbé, P. and M. Robin, 2006: Institutional adaptation of water resource infrastructure to climate change in Eastern Ontario. *Climatic Change*, **78**, 103-133.

Crane, T., 2013: *The Role of Local Institutions in Adaptive Processes to Climate Variability: The Cases of Southern Ethiopia and Southern Mali*. Oxfam Research Report, January 2013, Oxfam America, Boston, MA, USA, 34 pp.

Crichton, D., 2008: Role of insurance in reducing flood risk. *The Geneva Papers*, **33**, 117-132.

Dannevig, H., T. Rauken, and G. Hovelsrud, 2012: Implementing adaptation to climate change at the local level. *Local Environment*, **17(6-7)**, 597-611.

De Graaff, M.-A., C. Van Kessel, and J. Six, 2009: Rhizodeposition-induced decomposition increases N availability to wild and cultivated wheat genotypes under elevated CO_2. *Soil Biology and Biochemistry*, **41(6)**, 1094-1103.

Dessai, S., M. Hulme, R. Lempert, and R. Pielke Jr., 2009: Climate prediction: a limit to adaptation? In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, W.N., I. Lorenzoni, and K. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 64-78.

DeWulf, A., M. Mancero, G. Cárdenas, and D. Sucozhañay, 2011: Fragmentation and connection of frames in collaborative water governance: a case study of river catchment management in Southern Ecuador. *International Review of Administrative Sciences*, **77(1)**, 50-75.

Dinse, K., J. Read, and D. Scavia, 2009: *Preparing for Climate Change in the Great Lakes Region*. MICHU 09-103, Michigan Sea Grant, University of Michigan, Ann Arbor, MI, USA, 30 pp.

Dodman, D., 2012: *Developing Local Climate Change Plans: A Guide for Cities in Developing Countries*. Cities and Climate Change Initiative, United Nations Human Settlements Programme (UN-HABITAT) and International Institute for Environment and Development (IIED), UN-HABITAT, Nairobi, Kenya, 132 pp.

Dovers, S., 2009: Normalizing adaptation. Editorial. *Global Environmental Change*, **19**, 4-6.

Dovers, S.R. and R. Hezri, 2010: Institutions and policy processes: the means to the ends of adaptation. *Wiley Interdisciplinary Reviews: Climatic Change*, **1(2)**, 212-231.

Doyle, J.T., M.H. Redsteer, and M.J. Eggers, 2013: Exploring effects of climate change on Northern Plains American Indian health: *Climatic Change*, **120(3)**, 643-655.

Drabek, T., 1999: Understanding disaster warning responses. *The Social Science Journal*, **36(3)**, 515-523.

Dumaru, P., 2010: Community-based adaptation: enhancing community adaptive capacity in Drudrua Island, Fiji. *Wiley Interdisciplinary Reviews: Climate Change*, **1(5)**, 751-763.

Ebi, K.L., K.A. Exuzides, E. Lau, M. Kelsh, and A. Barnston, 2004: Weather changes associated with hospitalizations for cardiovascular diseases and stroke in California, 1983-1998. *International Journal of Biometeorology*, **49(1)**, 48-58.

EC, 2009: *Guidance Document No. 24: River Basin Management in a Changing Climate*. Common Implementation Strategy for the Water Framework Directive (2000/60/EC), Technical Report-2009-040, European Communities (EC), EC Publications Office, Luxembourg, Luxembourg, 134 pp.

EIRD, 2012: Cómo desarrollar ciudades más resilientes. Un manual para líderes de los gobiernos locales. Una contribución a la campana 2010-2015. Desarrollo de ciudades resilientes - ¡Mi ciudad está preparada! Estrategia Internacional de Naciones Unidas para la Reducción de Desastres, Ginebra, Suiza, 98 pp.

Engle, N.L., 2011: Adaptive capacity and its assessment. *Global Environmental Change*, **21(2)**, 647-656.

Engle, N.L. and M.C. Lemos, 2010: Unpacking governance: building adaptive capacity to climate change of river basins in Brazil. *Global Environmental Change*, **20(1)**, 4-13.

Ensor, J., and R. Berger, 2009: Community-based adaptation and culture in theory and practice. In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, W.N., I. Lorenzoni, and K.L. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 227-239.

Epstein, J.M. and R. Axtell, 1996: *Growing Artificial Societies – Social Science from the Bottom Up*. MIT Press, Cambridge, MA, USA, 224 pp.

Eriksen, S. and J. Lind, 2009: Adaptation as a political process: adjusting to drought and conflict in Kenya's drylands. *Environmental Management*, **43(5)**, 817-835.

ESPACE, 2008: *Climate Change Impacts and Spatial Planning Decision Support Guidance*. European Spatial Planning: Adapting to Climate Events (ESPACE) Project, Prepared by Halcrow, London, UK with the Environment Agency, The ESPACE Project, Environment Department, Winchester, Hampshire, UK, 30 pp., www.espace-project.org/publications/Extension%20Outputs/EA/Espace%20Final_Guidance_Finalv5.pdf.

Etkin, D., 1999: Risk transference and related trends: driving forces towards more mega-disasters. *Global Environmental Change B: Environmental Hazards*, **1(2)**, 69-75.

Etkin, D., J. Medalye, and K. Higuchi, 2012: Climate warming and natural disaster management: an exploration of the issues. *Climatic Change*, **112(3-4)**, 585-599.

Ewing, R., K. Bartholomew, S. Winkelman, J. Walters, and G. Anderson, 2008: Urban development and climate change. *Journal of Urbanism: International Research on Placemaking and Urban Sustainability*, **1(3)**, 201-216.

Falaleeva, M., C. O'Mahony, S. Gray, M. Desmond, J. Gault, and V. Cummins, 2011: Towards climate change adaptation and coastal governance in Ireland: Integrated architecture for effective management? *Marine Policy*, **35(6)**, 784-793.

Fankhauser, S. and I. Burton, 2011: Spending adaptation money wisely. *Climate Policy*, **11(3)**, 1037-1049.

Fankhauser, S., J.B. Smith, and R.S.J Tol, 1999: Weathering climate change: some simple rules to guide adaptation decisions. *Ecological Economics*, **30(1)**, 67-78.

Few, R., K. Brown, and E .Tompkins, 2007a: Climate change and coastal management decisions: insights from Christchurch Bay, UK. *Coastal Management*, **35(2-3)**, 255-270.

Few, R., K. Brown, and E.L Tompkins, 2007b: Public participation and climate change adaptation: avoiding the illusion of inclusion. *Climate Policy*, **7(1)**, 46-59.

Folke, C., T. Hahn, P. Olsson, and J. Norberg, 2005: Adaptive governance of social-ecological systems. *Annual Review of Environment and Resources*, **30**, 441-473.

Ford, J.D., L. Berrang-Ford, and J. Paterson, 2011: A systematic review of observed climate change adaptation in developed nations. *Climatic Change*, **106**, 327-336.

Foster, J., S. Winkelman, and A. Lowe, 2011: *Lessons Learned on Local Climate Adaptation from the Urban Leaders Adaptation Initiative*. Center for Clean Air Policy (CCAP), Washington, DC, USA, 23 pp.

Fouillet, A., G. Rey, V. Wagner, K. Laaidi, P. Empereur-Bissonnet, A. Le Tertre, P. Frayssinet, P. Bessemoulin, F. Laurent, P. De Crouy-Chanel, E. Jougla, and D. Hemon, 2008: Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave. *International Journal of Epidemiology*, **37(2)**, 309-317.

Freudenburg, W.R., R. Gramling., S. Laska, and K.T. Erikson, 2008: Organizing hazards, engineering disasters? Improving the recognition of political-economic factors in the creation of disasters. *Social Forces*, **87(2)**, 1015-1038.

Frommer, B., 2009: Climate change and the resilient society: utopia or realistic option for German regions? *Natural Hazards*, **58(1)**, 85-101.

Fujisawa, M. and K. Kobayashi, 2010: Apple (*Malus pumila var. domestica*) phenology is advancing due to rising air temperature in northern Japan. *Global Change Biology*, **16(10)**, 2651-2660.

Füssel, H.-M., 2007: Adaptation planning for climate change: concepts, assessment approaches, and key lessons. *Sustainability Science*, **2(2)**, 265-275.

Garrelts, H. and H. Lange, 2011: Path dependencies and path change in complex fields of action: climate adaptation policies in Germany in the realm of flood risk management. *AMBIO*, **40(2)**, 200-209.

Gautam, M.R., K. Chief, and W.J. Smith, 2013: Climate change in arid lands and Native American socioeconomic vulnerability: the case of the Pyramid Lake Paiute Tribe. *Climatic Change*, **120**, 585-599.

Geerts, S. and D. Raes, 2009: Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agricultural Water Management*, **96(9)**, 1275-1284.

Geiser, U. and S. Rist (eds.), 2009: *Decentralisation Meets Local Complexity: Local Struggles, State Decentralisation and Access to Natural Resources in South Asia and Latin America*. Perspectives of the Swiss National Centre of Competence in Research North-South (NCCR North-South), University of Bern, Vol. 4, NCCR North-South, Bern, Switzerland, 273 pp.

Gimblett, H.R. (ed.), 2002: *Integrating Geographic Information Systems and Agent-Based Modeling Techniques: For Simulating Social and Ecological Processes*. Oxford University Press, New York, NY, USA, 327 pp.

GIZ, 2012: *Insurance for Climate Change Adaptation Project*. A Project of the International Climate Initiative (ICI) of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) *GmbH*, on behalf of BMU, GIZ, Bonn, Germany, 8 pp., seguros.riesgoycambioclimatico.org/publicaciones/2012/ACC_ingles_internet.pdf.

GLA, 2011: *Managing Risks and Increasing Resilience: The Mayor's Climate Change Adaptation Strategy*. Greater London Authority (GLA), London, UK, 124 pp., www.london.gov.uk/sites/default/files/Adaptation-oct11.pdf.

Glaas, E. and S. Juhola, 2013: New levels of climate adaptation policy: analyzing the institutional interplay in the Baltic Sea Region. *Sustainability*, **5**, 256-275.

Glaas, E., A. Jonsson, M. Hjerpe, and Y. Andersson-Sköld, 2010: Managing climate change vulnerabilities: formal institutions and knowledge use as determinants of adaptive capacity at the local level in Sweden. *Local Environment: The International Journal of Justice and Sustainability*, **15(6)**, 525-539.

Gornitz, V., 2001: Sea-level rise and coasts. In: *Climate Change and a Global City: The Potential Consequences of Climate Variability and Change, Metro East Coast* [Rosenzweig, C. and W.E. Solecki (eds.)]. Report for the US Global Change Research Program, Columbia Earth Institute, New York, NY, USA, pp. 21-46.

Government of Nepal, 2011: *National Framework on Local Adaptation Plans for Action*. Government of Nepal, Ministry of Science, Technology and Environment, Department of Environment, Climate Change Management Division, Kathmandu, Nepal, 56 pp.

Granberg, M. and I. Elander, 2007: Local governance and climate change. *Local Environment*, **12**, 537-548.

Green, D. and G. Raygorodetsky, 2010: Indigenous knowledge of a changing climate. *Climatic Change*, **100**, 239-242.

Green, D., J. Billy, and A. Tapim, 2010: Indigenous Australians' knowledge of weather and climate: *Climatic Change*, **100**, 337-354.

Gupta, J., C. Termeer, J. Klostermann, S. Meijerink, M. van den Brink, P. Jong, S. Nooteboom, and E. Bergsma, 2010: The adaptive capacity wheel: a method to assess the inherent characteristics of institutions to enable the adaptive capacity of society. *Environmental Science & Policy*, **13(6)**, 459-471.

Haites, E. and C. Mwape, 2013: *Sources of Long-Term Climate Change Finance*. LDC Paper Series, Written by Oxford Climate Policy, as a partner institution of the European Capacity Building Initiative (ECBI), Oxford Climate Policy, Oxford, UK, 14 pp., ldcclimate.files.wordpress.com/2012/05/long-term-sources.pdf.

Hallegatte, S., 2008: An adaptive regional input-output model and its application to the assessment of the economic cost of Katrina. *Risk Analysis*, **28(3)**, 779-799.

Hallegatte, S., 2009: Strategies to adapt to an uncertain climate change. *Global Environment Change*, **19(2)**, 240-247.

Hamin, E. and N. Gurran, 2009: Urban form and climate change: balancing adaptation and mitigation in the U.S. and Australia. *Habitat International*, **33**, 238-245.

Handmer, J., 2009: Adaptive capacity: what does it mean in the context of natural hazards. In: *The Earthscan Reader in Adaptation to Climate Change* [Schipper, E.L.F. and I. Burton (eds.)]. Earthscan, London, UK, pp. 213-227.

Hardee, K. and C. Mutunga, 2010: Strengthening the link between climate change adaptation and national development plans: lessons from the case of population in National Adaptation Programmes of Action (NAPAs). *Mitigation and Adaptation Strategies for Global Change*, **15**, 113-126.

Hardoy, J. and G. Pandiella, 2009: Urban poverty and vulnerability to climate change in Latin America. *Environment and Urbanization*, **21(1)**, 203-224.

Harries, T. and E. Penning-Rowsell, 2011: Victim pressure, institutional inertia, and climate change adaptation: the case of flood risk. *Global Environmental Change*, **21**, 188-197.

Hedensted Lund, D., K. Sehested, T. Hellesen, and V. Nelleman, 2012: Climate change adaptation in Denmark: enhancement through collaboration and meta-governance. *Local Environment*, **17(6)**, 613-628.

Hinkel, J., S. Bisaro, T. Downing, M.E. Hofmann, K. Lonsdale, D. Mcevoy, and D. Tabara, 2009: Learning to adapt. Narratives of decision makers adapting to climate change. In: *Making Climate Change Work for Us: European Perspectives on Adaptation and Mitigation Strategies* [Hulme, M. and H. Neufeldt (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp.113-134.

Hodson, M. and S. Marvin, 2009: Urban ecological security: a new urban paradigm? *International Journal of Urban and Regional Research*, **33(1)**, 193-215.

Hofmann, M., J. Hinkel, and M. Wrobel, 2011: Classifying knowledge on climate change impacts, adaptation and vulnerability in Europe for informing adaptation research and decision-making: a conceptual meta-analysis. *Global Environmental Change*, **21(3)**, 1106-1116.

Hofstede, J., 2008: Climate change and coastal adaptation strategies: the Scheswig-Holstein perspective. *Baltica*, **21(1-2)**, 71-78.

Holden, M., 2008: Social learning in planning: Seattle's sustainable development codebooks. *Progress in Planning*, **69**, 1-40.

Howe, P., 2011: Hurricane preparedness as anticipatory adaptation: a case study of community businesses. *Global Environmental Change*, **2**, 711-720.

Hulme, M., H. Neufeldt, H. Colyer, and A. Ritchie (eds.), 2009: *Adaptation and Mitigation Strategies: Supporting European Climate Policy.* The Final Report from the ADAM Project, Revised June 2009, Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, UK, 47 pp.

Huntjens, P., C. Pahl-Wostl, Z. Flachner, S. Neto, R. Koskova, M. Schlueter, I. NabideKiti, and C. Dickens, 2011: Adaptive water management and policy learning in a changing climate. A formal comparative analysis of eight water regimes in Europe, Asia, and Africa. *Environmental Policy Governance*, **21(3)**, 145-163.

Huntjens, P., L. Lebel, C. Pahl-Wostl, J. Camkin, R. Schulze, and N. Kranz, 2012: Institutional design propositions for the governance of adaptation to climate change in the water sector. *Global Environmental Change*, **22**, 67-81.

IAPAD, 2010: *Participatory 3 Dimensional Modelling – Integrated Approaches to Participatory Development*. Integrated Approaches to Participatory Development (IAPAD), www.iapad.org/participatory_p3dm.htm.

ICLEI, 2008: *Cities for Climate Protection Australia Adaptation Initiative – Local Government Climate Change Adaptation Toolkit*. ICLEI – Local Governments for Sustainability (ICLEI), Regional Secretariat, ICLEI Oceania, Melbourne, VC, Australia, 61 pp.

IFRC, Red Cross / Red Crescent Climate Centre, and ProVention Consortium, 2009: *Climate Change Adaptation Strategies for Local Impact: Key Messages for UNFCCC Negotiators*. Technical Paper for the IASC Task Force on Climate Change, International Federation of Red Cross and Red Crescent Societies (IFRC), Red Cross / Red Crescent Climate Centre and ProVention Consortium in collaboration with Ken Westgate, 11 pp., unfccc.int/resource/docs/2009/smsn/igo/054.pdf.

IISD, 2012: *CRiSTAL User's Manual Version 5: Community-based Risk Screening Tool – Adaptation and Livelihoods*. The International Institute for Sustainable Development (IISD), International Union for Conservation of Nature (IUCN), Helvetas Swiss Intercooperation, and Stockholm Environment Institute (SEI), IISD, Winnipeg, MB, Canada, 55 pp.

Inderberg, T.H. and P.O. Eikeland, 2009: Limits to adaptation: analysing institutional constraints. In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, N.W., I. Lorenzoni, and K. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 443-447.

IPCC, 2007: *Climate Change 2007: Synthesis Report*. *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K and A. Reisinger (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. *A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [C.B., Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp.

IPCC-TGICA, 2007: *General Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment*. Version 2, Prepared by T.R. Carter on behalf of the Intergovernmental Panel on Climate Change, Task Group on Data and Scenario Support for Impact and Climate Assessment (TGICA), 66 pp.

ISDR, 2005: *Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters*. World Conference on Disaster Reduction, 18-22 January 2005, Kobe, Hyogo, Japan, The United Nations Secretariat of the International Strategy for Disaster Reduction (UNISDR), Geneva, Switzerland, 22 pp., http://www.unisdr.org/files/1037_hyogoframeworkforactionenglish.pdf.

ISDR, 2011: *Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters – Mid-Term Review 2010-2011*. The International Strategy for Disaster Reduction (ISDR), The United Nations Secretariat of the International Strategy for Disaster Reduction (UNISDR), Geneva, Switzerland, 107 pp.

ISDR, ITC, and UNDP, 2010: *Local Governments and Disaster Risk Reduction: Good Practices and Lessons Learned*. Contribution to the "Making Cities Resilient" Campaign, The International Strategy for Disaster Reduction (ISDR), International Training Centre (ITC), and United Nations Development Programme (UNDP), the United Nations Secretariat of International Strategy for Disaster Reduction (UNISDR), Geneva, Switzerland, 69 pp.

Jones, L. and E. Boyd, 2011: Exploring social barriers to adaptation: insights from Western Nepal. *Global Environmental Change*, **21**, 1262-1274.

Jonkman, S.N., A. Lentz, and J.K. Vrijling, 2010: A general approach for the estimation of loss of life due to natural and technological disasters. *Reliability Engineering and System Safety*, **95**, 1123-1133.

Jonsson, E.C., M. Hjerpe, Y. Andersson-Sköld, E. Glaas, K. André, and L. Simonsson, 2012: Cities' capacity to manage climate vulnerability: experiences from participatory vulnerability assessments in the lower Göta Älv Catchment, Sweden. *Local Environment*, **17(6)**, 735-750.

Juhola, S. and L. Westerhoff, 2011: Challenges of adaptation to climate change across multiple scales: a case study of network governance in two European countries. *Environmental Science & Policy*, **14(3)**, 239-247.

Julius, S.H. and J.D. Scheraga, 2000: The TEAM model for evaluating alternative adaptation strategies. In: *Research and Practice in Multiple Criteria Decision Making* [Haimes, Y.Y. and R.E. Steuer (eds.)]. Springer-Verlag, New York, NY, USA, pp. 319-30.

Kabat, P., L.O. Fresco, M.J.C. Stive, C.P. Veerman, J.S.L.J. van Alphen, B.W.A.H. Parmet, W. Hazeleger, and C.A. Katsman, 2009: Dutch coast in transition. *Nature Geoscience*, **2**, 450-452.

Kalame, F., D. Kudejira, and J. Nkem, 2011: Assessing the process and options for implementing National Adaptation Programmes of Action (NAPA): a case study from Burkina Faso. *Mitigation and Adaptation Strategies for Global Change*, **16(5)**, 535-553.

Kalanda-Joshua, M., C. Ngongondo, L. Chipeta, and F. Mpembeka, 2011: Integrating Indigenous knowledge with conventional science: enhancing localized climate and weather forecasts in Nessa, Mulanje, Malawi. *Physics and Chemistry of the Earth, Parts A/B/C*, **36(14-15)**, 996-1003.

Kaner, S., L. Lind, C.Toldi, S. Fisk, and D. Berger, 2007: *Facilitator's Guide to Participatory Decision-Making*. 2nd edn., Jossey-Bass, San Francisco, CA, USA, 368 pp.

Karanasios, S., 2011: *New & Emergent ICTs and Climate Change in Developing Countries*. Centre for Development Informatics, Institute for Development Policy and Management, SED, University of Manchester, Manchester, UK, 39 pp.

Karl, T.R., J.M. Melillo, and T.C. Peterson, 2009: *Global Climate Change Impacts in the United States*. U.S. Global Change Research Program (USGCRP), Cambridge University Press, New York, NY, USA, 188 pp.

Kaslo and Regional District of Central Kootenay Partnership, 2010: *Kaslo / Area D Climate Change Adaptation Project*. Kaslo/RDCK Area D Partnership, Climate Change Adaptation & You, jointly funded by Columbia Basin Trust (CBT), Regional District of Central Kootenay (RDCK) and the Village of Kaslo, CBT, Nakusp, BC, Canada, 12 pp., www.cbt.org/uploads/pdf/RDCK_Area_D_Kaslo_Phase_2_CACCI_Final_report.pdf.

Keskitalo, E.C.H., 2009: Governance in vulnerability assessments: the role of globalizing decision-making networks in determining local vulnerability and adaptive capacity. *Mitigation and Adaptation Strategies for Global Change*, **14**, 185-201.

Keskitalo, E.C.H. and A.A. Kulyasova, 2009: The role of governance in community adaptation to climate change. *Polar Research*, **28**, 60-70.

Klein, R.J.T., S.E.H. Eriksen, L.O. Næss, A. Hammill, T.M. Tanner, C. Robledo, and K.L. O'Brien, 2007: Portfolio screening to support the mainstreaming of adaptation to climate change into development assistance. *Climatic Change*, **84(1)**, 23-44

Koch, I.C., C. Vogel, and Z. Patel, 2007: Institutional dynamics and climate change adaptation in South Africa. *Mitigation and Adaptation Strategies for Global Change*, **12(8)**, 1323-1339.

Lasco, R., F. Pulhin, P. Jaranilla-Sanchez, R. Delfino, R. Gerpacio, and K. Garcia, 2009: Mainstreaming adaptation in developing countries: the case of the Philippines. *Climate and Development*, **1**, 130-146.

Lasco, R.D., C.M.D. Habito, R.J.P. Delfino, F.B. Pulhin, and R.N. Conception, 2011: *Climate Change Adaptation for Smallholder Farmers in Southeast Asia.* World Agroforestry Centre, Laguna, Philippines, 65 pp.

Lemmen, D.S., F.J. Warren, J. Lacroix, and E. Bush (eds.), 2008: *From Impacts to Adaptation: Canada in a Changing Climate 2007*. Government of Canada, Climate Change Impacts and Adaptation Division, Earth Sciences Sector, Natural Resources Canada, Ottawa, ON, Canada, 448 pp.

Lemos, M.C., E. Boyd, E. Tompkins, H. Osbahr, and D. Liverman, 2007: Developing adaptation and adapting development. *Ecology and Society*, **12(2)**, 26, www.ecologyandsociety.org/vol12/iss2/art26/.

Leonard, S., M. Parsons, K. Olawsky, and F. Kofod, 2013: The role of culture and traditional knowledge in climate change adaptation: insights from east Kimberley, Australia. *Global Environmental Change*, **23(3)**, 623-632.

Li, Y. and M. Li, 2009: A study on the construction of water resources regulation decision support system of the Yellow River. *Areal Research and Development*, **28(5)**, 140-144. (in Chinese)

Link, L.E., 2010: The anatomy of a disaster, an overview of Hurricane Katrina and New Orleans. *Ocean Engineering*, **37**, 4-12.

Linnerooth-Bayer, J., R. Mechler, and S. Hochrainer, 2011: Insurance against losses from natural disasters in developing countries. Evidence, gaps and the way forward. *Journal of Integrated Disaster Risk Management*, **1(1)**, 1-23.

Lowe, A., J. Foster, and S. Winkelman, 2009: *Ask the Climate Question: Adapting to Climate Change Impacts in Urban Regions*. Center for Clean Air Policy (CCAP), Washington, DC, USA, 44 pp.

Majule, A.E., T. Stathers, R. Lamboll, E.T. Liwenga, C. Ngongondo, M. Klanda-Joshua, E. Swai, and F. Chipungu, 2013: Enhancing capacities of individuals, institutions and organizations to adapt to climate change in agricultural sector using innovative approaches in Tanzania and Malawi. *World Journal of Agricultural Sciences*, **1(6)**, 220-231.

Manuel-Navarrete, D., M. Pelling, and M. Redclift, 2009: *Coping, Governance, and Development: The Climate Change Adaptation Triad*. Environment, Politics and Development Working Paper Series, WP No.18, Department of Geography, King's College London, London, UK, 17 pp.

Marongwe, L.S., K. Kwazira, M. Jenrich, C. Thierfelder, A. Kassam, and T. Friedrich, 2011: An African success: the case of conservation agriculture in Zimbabwe. *International Journal of Agricultural Sustainability*, **9(1)**, 153-161.

Masindel, M., A. Bagula, and N. Muthama, 2013: Implementation roadmap for downscaling drought forecasts in Mbeere using ITIKI. In: *Proceedings of the 2013 ITU Kaleidoscope Academic Conference: "Building Sustainable Communities," Kyoto, Japan, 22-24 April 2013*. IEEE Catalogue Number: CFP1138E-ART, International Telecommunication Union (ITU), Geneva, Switzerland, pp. 63-70.

Mathew, S., S. Trück, and A. Henderson-Sellers, 2012: Kochi, India case study of climate adaptation to floods: ranking local government investment options. *Global Environmental Change*, **22**, 308-319.

Matthews, T., 2012: Responding to climate change as a transformative stressor through metro-regional planning. *Local Environment*, **17(10)**, 1089-1103.

McGray, H., A. Hammill, R. Bradley, E.L. Schipper, and J.-E. Parry, 2007: *Weathering the Storm: Options for Framing Adaptation and Development*. World Resources Institute (WRI), Washington, DC, USA, 57 pp.

McLeman, R., D. Mayo, E. Strebeck, and B. Smit, 2008: Drought adaptation in rural eastern Oklahoma in the 1930s: lessons for climate change adaptation research. *Mitigation and Adaptation Strategies for Global Change*, **13(4)**, 379-400.

McNeeley, S.M., 2012: Examining barriers and opportunities for sustainable adaptation to climate change in Interior Alaska. *Climatic Change*, **111**, 835-857.

Measham, T., B. Preston, C. Brook, T. Smith, C. Morrisonn, G. Withycombe, and R. Gorddard, 2010: *Adapting to Climate Change through Local Municipal Planning: Barriers and Opportunities*. CSIRO Socio-Economics and the Environment in Discussion, CSIRO Working Paper Series 2010-05, The Commonwealth Scientific and Industrial Research Organisation (CSIRO), Canberra, Australia, 25 pp.

Measham, T.G., B.L. Preston, T.F. Smith, C. Brooke, R. Gorddard, G. Withycombe, and C. Morrison, 2011: Adapting to climate change through local municipal planning: barriers and challenges. *Mitigation and Adaptation Strategies for Global Change*, **16(8)**, 889-909.

Mees, H., P. Driessen, and H. Runhaar, 2012: Exploring the scope of public and private responsibilities for climate adaptation. *Journal of Environmental Policy and Planning*, **14(3)**, 305-330.

Michel-Kerjan, E. and H. Kunreuther, 2011: Redesigning flood insurance. *Science*, **333**, 408-409.

Mickwitz, P., F. Aix, S. Beck, D. Carss, N. Ferrand, C. Görg, A. Jensen, P. Kivimaa, C. Kuhlicke, W. Kuindersma, M. Máñez, M. Melanen, S. Monni, A.B. Pedersen, H. Reinert, and S. van Bommel, 2009: *Climate Policy Integration, Coherence and Governance*. PEER Report 2, Partnership for European Environmental Research (PEER), Helsinki, Finland, 92 pp.

Mills, E., 2004: *Insurance as an Adaptation Strategy for Extreme Weather Events in Developing Countries and Economies in Transition*. Prepared for the Agency for International Development Bureau for Economic Growth, Agriculture and Trade Office of Environment and Science Policy Climate Change Team, University of California, Lawrence Berkeley National Laboratory, Berkeley, CA, USA, 128 pp.

Miron, L., 2008: Transnational, national, and indigenous racial subjects. In: *Handbook of Critical and Indigenous Methodologies* [Denzin, N.K., Y.S. Lincoln, and L.T. Smith (eds.)]. SAGE Publications, Thousand Oaks, CA, USA, pp. 547-562.

Mitchell, T., M. van Aalst, and P.S. Villanueva, 2010: *Assessing Progress on Integrating Disaster Risk Reduction and Climate Change Adaptation in Development Processes*. Strengthening Climate Resilience Discussion Paper 2, Institute of Development Studies (IDS) at the University of Sussex, Brighton, UK, 28 pp.

Moriondo, M., M. Bindi, Z.W. Kundzewicz, M. Szwed, A. Chorynski, P. Matczak, M. Radziejewski, D. McEvoy, and A. Wreford, 2010: Impact and adaptation opportunities for European agriculture in response to climate change and variability. *Mitigation and Adaptation Strategies for Global Change*, **15(7)**, 657-679.

Moser, C., 2008: Assets and livelihoods: a framework for asset-based social policy. In: *Assets, Livelihoods, and Social Policy* [Moser, C. and A. Dani (eds.)]. World Bank, Washington, DC, USA, pp. 44-84.

Moser, C. and D. Satterthwaite, 2008: *Towards Pro-Poor Adaptation to Climate Change in the Urban Centers of Low- and Middle-Income Countries*. Climate Change and Cities Discussion Paper 3, Human Settlements Programme, International Institute for Environment and Development (IIED), London, UK, 45 pp.

Moser, S.C., 2005: Impacts assessments and policy responses to sea-level rise in three U.S. states: an exploration of human dimension uncertainties. *Global Environmental Change*, **15**, 353-369.

Moser, S.C., 2010: Now more than ever: the need for more societally relevant research on vulnerability and adaptation to climate change. *Applied Geography*, **30(4)**, 464-474.

Moser, S.C. and J.A. Ekstrom, 2010: A framework to diagnose barriers to climate change adaptation. *Proceedings of the National Academy of Sciences of the United States of America,* **107**, 22026-22031.

Mozumder, P., E. Flugman, and T. Randhir, 2011: Adaptation behavior in the face of climate change: survey responses from experts and decision makers serving the Florida Keys. *Ocean and Coastal Management*, **54**, 37-44.

Mugabe, F.T., A. Munodawafa, J. Dimes, D.H. Nanja, P. Carberry, M. Mwale, C. Mubaya, V. Makuvaro, I. Chagonda, P. Masere, E. Mutswangwa, and C. Murewi, 2010: *Building Adaptive Capacity to Cope with Increasing Vulnerability Due to Climate Change*. Final Technical Report, Climate Change and Adaptation in Africa (CCAA), IDRC Project Number: 104144, International Development Research Centre (IDRC), Ottawa, ON, Canada 175 pp.

Mukheibir, P., N. Kuruppu, A. Gero, and J. Herriman, 2013: *Cross-Scale Barriers to Climate Change Adaptation in Local Government, Australia*. National Climate Change Adaptation Research Facility (NCCARF), Griffith University, Gold Coast Campus, Southport, Australia, 95 pp.

Mullan, M., N. Kingsmill, A.M. Kramer, and S. Agrawala, 2013: *National Adaptation Planning: Lessons from OECD Countries*. OECD Environment Working Papers, No. 54, ENV/WKP(2013)1, OECD Publishing, Paris, France, 74 pp.

Naidoo, T., K. Vaz, and L. Byaba, 2012: *CTI PFAN Background Paper on Adaptation*. Climate Technology Initiative (CTI) Private Financing Advisory Network (PFAN), CTI Programme Secretariat, International Center for Environmental Technology Transfer (ICETT), Yokkaichi, Japan, 51 pp., www.cti-pfan.net/upload/event/file/CTIPFANAdaptationPaper_Final_270212.pdf.

Nakashima, D.J., K. Galloway McLean, H.D. Thulstrup, A. Ramos Castillo, and J.T. Rubis, 2012: *Weathering Uncertainty: Traditional Knowledge for Climate Change Assessment and Adaptation.* United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris, France and the United Nations University (UNU), Darwin, Australia, pp. 38-51.

Næss, L.O., G. Bang, S. Eriksen, and J. Vevatne, 2005: Institutional adaptation to climate change: flood responses at the municipal level in Norway. *Global Environmental Change*, **15(2)**, 125-138.

Nath, P.K. and B. Behera, 2011: A critical review of impact and adaptation to climate change in developed and developing economies, *Environmental Development and Sustainability*, **13**, 141-162.

National Research Council, 2011: *Adapting to the Impacts of Climate Change*. America's Climate Choices: Panel on Adapting to the Impacts of Climate Change, National Research Council, the National Academies Press, Washington, DC, USA, 272 pp.

NYCDEP, 2008: *Assessment and Action Plan – A Report Based on the Ongoing Work of the DEP Climate Change Task Force*. Report 1, The New York City Department of Environmental Protection Climate Change Program (NYCDEP), the New York City Department of Environmental Protection (DEP) with contributions by Columbia University Center for Climate Systems Research, the NASA Goddard Institute for Space Studies, HydroQual Environmental Engineers & Scientists, P.C., the New York City Office of Environmental Coordination, the Mayor's Office of Long-Term Planning and sustainability, and the New York City Law Department, DEP, New York, NY, USA, 100 pp., www.nyc.gov/html/dep/pdf/climate/climate_complete.pdf.

Newsham, N.J. and D.S.G. Thomas, 2011: Knowing, farming and climate change adaptation in North-Central Namibia. *Global Environmental Change*, **21**, 761-770.

Nilsson, A.E., Å.G. Swartling, and K. Eckerberg, 2012: Knowledge for local climate change adaptation in Sweden: challenges in multilevel governance. *Local Environment: The International Journal of Justice and Sustainability*, **17(6-7)**, 751-767.

National Research Council (NRC), 2010: *Adapting to the Impacts of Climate Change*. America's Climate Choices: Panel on Adapting to Impacts of Climate Change, National Research Council, National Academies Press, Washington, DC, USA, 272 pp.

O'Brien, G., P. O' Keefe, H. Meena, J. Rose, and L. Wilson, 2008: Climate adaptation from a poverty perspective. *Climate Policy*, **8(2)**, 194-201.

O'Brien, K. and J.A. Wolf, 2010: A values-based approach to vulnerability and adaptation to climate change. *WIREs Climate Change*, **1(2)**, 232-242.

O'Brien, K., S. Eriksen, L. Sygna, and L.O. Næss, 2006: Questioning complacency: climate change impacts, vulnerability, and adaptation in Norway. *Ambio*, **35**, 50-56.

O'Brien, K., M. Pelling, A. Patwardhan, S. Hallegatte, A. Maskrey, T. Oki, U. Oswald-Spring, T. Wilbanks, and P.Z. Yanda, 2012: Toward a sustainable and resilient future. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 437-486.

O'Demsey, T., 2009: Fair training: a new direction in humanitarian assistance. *Progress in Development Studies*, **9(1)**, 81-86.

OECD, 2009: *Integrating Climate Change Adaptation into Development Co-operation*, Policy Guidance, OECD Publishing, Paris, France, 193 pp.

Olesen, J., M. Tranka, K. Kersebaum, A. Skjelvag, B. Seguin, P. Peltonen-Sainio, F. Rossi, J. Kozyra, and F. Micale, 2011: Impacts and adaptation of European crop production systems to climate change. *European Journal of Agronomy*, **34**, 96-112.

Oort, P., 2012: Why farmers' sowing dates hardly change when temperature rises. *European Journal of Agronomy*, **40**, 102-111.

Orlove, B., 2009: The past, the present and some possible futures of adaptation. In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, W.N., I. Lorenzoni, and K. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 131-162.

Ospina, A.V. and R. Heeks, 2010: *Linking ICTs and Climate Change Adaptation: A Conceptual Framework for e-Resilience and e-Adaptation*. Centre for Development Informatics, Institute for Development Policy and Mangement, SED, University of Manchester, Manchester, UK, 39 pp.

Ostrom, E., 1990: *Governing the Commons: The Evolution of Institutions for Collective Action*. The Political Economy of Institutions and Decisions, Cambridge University Press, Cambridge, UK, 280 pp.

Owen, S., 2010: Learning across levels of governance: expert advice and the adoption of carbon dioxide emissions reduction targets in the UK. *Global Environmental Change*, **20(3)**, 394-401.

Oxfam, 2009: *Horn of Africa Risk Transfer for Adaptation (HARITA)*. Project Brief, August, 2009, Oxfam America, Boston, MA, USA, 7 pp., iri.columbia.edu/~deo/HARITAUpdateAugust112009short.pdf.

Oxfam International, 2009: *Bolivia: Climate Change, Poverty and Adaptation*. Oxfam International, La Paz, Bolivia, 67 pp.

Pahl-Wostl, C., 2009: A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. *Global Environmental Change*, **19(3)**, 354-365.

Park, S.E., N.A. Marshall, E. Jakku, A.M. Dowd, S.M. Howden, E. Mendham, and A. Fleming, 2012: Informing adaptation responses to climate change through theories of transformation. *Global Environmental Change*, **22**, 115-126.

Parry, M., N. Arnell, P. Berry, D. Dodman, S. Fankhauser, C. Hope, S. Kovats, R. Nicholls, D. Satterthwaite, R. Tiffin, and T. Wheeler, 2009: *Assessing the Costs of Adaptation to Climate Change: A Review of the UNFCCC and Other Recent Estimates*. International Institute for Environment and Development (IIED) and the Grantham Institute for Climate Change, Imperial College London, London, UK, 111 pp.

Parzen, J., 2009: *Lessons Learned: Creating the Chicago Climate Action Plan*. Commissioned by the City of Chicago, Department of Environment, Chicago, IL, USA, 37 pp., www.chicagoclimateaction.org/filebin/pdf/LessonsLearned.pdf.

Patt, A.G. and D. Schröter, 2008: Perceptions of climate risk in Mozambique: implications for the success of adaptation strategies, *Global Environmental Change*, **18(3)**, 458-467.

Paudel, Y., 2012: A comparative study of public-private catastrophe insurance systems: lessons from current practices. *The Geneva Papers*, **37**, 257-285.

Peach Brown, H.C., B. Smit, O.A. Somorin, D.J. Sonwa, and F. Ngana, 2013: Institutional perceptions, adaptive capacity and climate change responses in a post-conflict country: a case study from Central African Republic. *Climate and Development*, **5(3)**, 206-216.

Pelling, M., 2011: *Adaptation to Climate Change: from Resilience to Transformation*. Routledge Press, London and New York, 203 pp.

Pelling, M., C. High, J. Dearing, and D. Smith, 2008: Shadow spaces for social learning: a relational understanding of adaptive capacity to climate change within organisations. *Environment and Planning A*, **40**, 867-884.

Pew Centre on Global Climate Change, 2009: *Adaptation Planning – What U.S. States and Localities Are Doing*. Prepared for the Pew Center on Global Climate Change by T. Cruce, November 2007 (Updated August 2009), Arlington, VA, USA, 25 pp., www.pewclimate.org/working-papers/adaptation.

Picard, P., 2008: Natural disaster insurance and the equity-efficiency trade-off. *Journal of Risk and Insurance*, **75**, 17-38.

Picketts, I., A. Werner, T. Murdock, J. Curry, S. Dery, and D. Dyer, 2012: Planning for climate change adaptation: lessons learned from a community-based workshop. *Environmental Science and Policy*, **17**, 82-93.

Pinoleville Pomo Nation, 2013: *Sustainable Housing Program Information Sheet*, Pinoleville Pomo Nation Housing Authority, Ukiah, CA, USA, 2 pp., www.sustainablenativecommunities.org/fieldnews/wp-content/uploads/2013/07/130611_07_CS-HUD-Pinoleville-Pomo-Nation-Homes.pdf.

PPCR, 2013: *PPCR Pilot Country Updates October 2012 – April 2013*. The Pilot Program for Climate Resilience (PPCR), a targeted program of the Strategic Climate Fund (SCF), within the framework of the Climate Investment Funds (CIF), The World Bank Group, Washington, DC, USA, 67 pp., https://www.climateinvestmentfunds.org/cif/sites/climateinvestmentfunds.org/files/PPCR_SC.13_Inf.2_Updates_from_PPCR_Pilot_Countries.pdf.

Preston, B.L., R. Westaway, S. Dessai, and T.F. Smith, 2009: *Are We Adapting to Climate Change? Research and Method for Evaluating Progress*. Presentation at the 89th American Meteorological Society Annual Meeting – Fourth Symposium on Policy and Socio-Economic Research, 10-16 January 2009, Phoenix, AZ, USA, 1.1, 15 pp., ams.confex.com/ams/89annual/techprogram/programexpanded_524.htm.

Preston, B.L., R.M. Westaway, and E.J. Yuen, 2011: Climate adaptation planning in practice: an evaluation of adaptation plans from three developed nations. *Mitigation and Adaptation Strategies for Global Change*, **16**, 407-438.

Preston, B.L., K. Dow, and F. Berkhout, 2013: The climate adaptation frontier. *Sustainability*, **5**, 1011-1035.

Pringle, P., 2011: *AdaptME: Adaptation Monitoring and Evaluation*. United Kingdom Climate Impacts Programme (UKCIP), School of Geography and the Environment, Oxford University Centre for the Environment (OUCE), University of Oxford, Oxford, UK, 37 pp.

Prober, S., M. O'Connor, and F. Walsh, 2011: Australian aboriginal peoples' seasonal knowledge; a potential basis for shared understanding in environmental management. *Ecology and Society*, **16(2)**, 12, www.ecologyandsociety.org/vol16/iss2/art12/.

Pulwarty, R., C. Simpson, and C. Nierenberg, 2009: Regional Integrated Sciences and Assessments (RISAs): crafting assessments for the long haul. In: *Integrated Regional Assessments of Global Climate Change* [Knight, G. and J. Jager, (eds.)]. Cambridge Press, Cambridge, UK, pp. 367-394.

Pulwarty, R., L. Nurse, and N. Trotz, 2010: Caribbean Islands in a changing climate. *Environment*, November-December, 2010, **52**, 16-27, www.environmentmagazine.org/Archives/Back%20Issues/November-December%202010/caribbean-islands-full.html.

Pulwarty, R., G. Eilerts, and J. Verdin, 2012: Food security in a changing climate. *Solutions: For a Sustainable & Desirable Future*, **3(1)** 31-34.

Pulwarty, R. and J. Verdin, 2013: Crafting early warning systems. In: *Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies* [Birkmann (ed.)]. United Nations University Press, Tokyo, Japan, pp. 124-147.

Pyke, C.R., B.G. Bierwagen, J. Furlow, J. Gamble, T. Johnson, S. Julius, and J. West, 2007: A decision inventory approach for improving decision support for climate change impact assessment and adaption. *Environmental Science & Policy*, **10**, 610-621.

Ranger, N. and S. Surminski, 2013: A preliminary assessment of the impact of climate change on non-life insurance demand in the BRICS economies. *International Journal of Disaster Risk Reduction*, **3**, 14-30.

Raschky, P., 2008: Institutions and the losses from natural disasters. *Natural Hazards and Earth System Sciences*, **8**, 627-634.

Rawlani, A. and B. Sovacool, 2011: Building responsiveness to climate change through community based adaptation in Bangladesh. *Mitigation and Adaptation Strategies for Global Change*, **16(8)**, 845-863.

Redsteer, M.H., K.B. Kelley, H. Francis, and D. Block, 2010: Disaster risk assessment case study: recent drought on the Navajo Nation, Southwestern United States. Background Paper for Chapter 3 of the Global Assessment Report on Diaster Risk Reduction 2011, The International Strategy for Disaster Reduction (ISDR) and U.S. Geological Survey (USGS), The United Nations Secretariat of the International Strategy for Disaster Reduction (UNISDR), Geneva, Switzerland, 19 pp. www.preventionweb.net/english/hyogo/gar/2011/en/what/drought.html.

Redsteer, M.H., K. Bemis, K. Chief, M. Gautam, B.R. Middleton, and R. Tsosie, 2013: Chapter 17: Unique challenges facing southwestern tribes: impacts, adaptation and mitigation. In: *Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment* [Garfin, G., A. Jardine, R. Merideth, M. Black, and S. LeRoy (eds.)]. A report by the Southwest Climate Alliance, Island Press, Washington, DC, USA, pp. 385-404.

Reid, H., D. Dodman, R. Janssen, and S. Huq, 2010: Building capacity to cope with climate change in the least developed countries. In: *Changing Climates, Earth Systems and Society* [Dodson, J. (ed.)]. Springer, New York, NY, USA, pp. 217-230.

Repetto, R., 2008: *The Climate Crisis and the Adaptation Myth*. Working Paper No. 13, Yale School of Forestry and Environmental Studies, New Haven, CT, USA, 21 pp.

Revi, A., 2008: Climate change risks: an adaptation and mitigation agenda for Indian cities. *Environment and Urbanization*, **20(1)**, 207-229.

Ribot, J.C., 2010: Vulnerability does not fall from the sky: toward multi-scale pro-poor climate policy. In: *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World* [R. Mearns and A. Norton (eds.)]. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, pp. 47-74.

Ribot, J., 2011: Vulnerability before adaptation: towards transformative climate action. *Global Environmental Change*, **21**, 1160-1162.

Roberts, D., 2008: Think globally, acting locally – institutionalizing climate change at the local government level in Durban, South Africa. *Environment and Urbanization*, **20(2)**, 521-537.

Roberts, D., 2010: Prioritizing climate change adaptation and local level resilience in Durban, South Africa. *Environment and Urbanization*, **22**, 397-413.

Robinson, L.W. and F. Berkes, 2011: Multi-level participation for building adaptive capacity: formal agency-community interactions in northern Kenya. *Global Environmental Change*, **21**, 1185-1194.

Rodima-Taylor, D., M.F. Olwig, and N. Chhetri, 2012: Adaptation as innovation, innovation as adaptation: an institutional approach to climate change, *Applied Geography*, **33**, 107-111.

Romani, M. and N. Stern, 2013: Chapter 7: Sources of finance for climate action: principles and options for implementation mechanisms in this decade. In: *International Climate Finance* [E. Haites (ed.)]. Routledge, New York, NY, USA, pp. 117-134.

Romero-Lankao, P., 2012: Governing carbon and climate in the cities: an overview of policy and planning challenges and options. *European Planning Studies*, **20**, 7-26.

Romero-Lankao, P. and D. Dodman, 2011: Cities in transition: transforming urban centers from hotbeds of GHG emissions and vulnerability to seedbeds of sustainability and resilience: introduction and editorial overview. *Current Opinion in Environmental Sustainability*, **3(3)**, 113-120.

Rosenzweig, C. and W. Solecki, (eds.), 2010: Climate change adaptation in New York City: building a risk management response: New York City Panel on Climate Change 2010 report. *Annals of the New York Academy of Sciences*, **1196**, 1-354.

Rosenzweig, C., W.D. Solecki, R. Blake, M. Bowman, C. Faris, V. Gornitz, R. Horton, K. Jacob, A. LeBlanc, R. Leichenko, M. Linkin, D. Major, M. O'Grady, L. Patrick, E. Sussman, G. Yohe, and R. Zimmerman, 2011: Developing coastal adaptation to climate change in the New York City infrastructure-shed: process, approach, tools, and strategies. *Climatic Change*, **106(1)**, 93-127.

Rumbach, A.J. and N. Kudva, 2011: Putting people at the center of climate change adaptation plans: a vulnerability approach. *Risks, Hazards & Crisis in Public Policy*, **2(4)**, 1-23.

Runhaar, H., H. Mees, A. Wardekker, J. van der Sluis, and P. Driessen, 2012: Adaptation to climate change-related risks in Dutch urban areas: stimuli and barriers. *Regional Environmental Change*, **12(4)**, 777-790.

Sabates-Wheeler, R., T. Mitchell, and F. Ellis, 2008: Avoiding repetition: time for community based adaptation to engage with the livelihoods literature? *IDS Bulletin*, **39**, 53-59.

Sanchez-Rodriguez, R., 2009: Learning to adapt to climate change in urban areas. A review of recent contributions. *Current Opinion in Environmental Sustainability*, **1**, 201-206.

Sanchez-Rodriguez, R., 2012: Understanding and improving urban responses to climate change. Reflections for an operational approach to adaptation in low and middle-income countries. In: *Cities and Climate Change. Responding to an Urgent Agenda* [D. Hoornweg, M. Freire, M. J. Lee, P. Bhada-Tata, B. Yuen, (eds.)]. The World Bank, Washington, DC, USA, pp. 452-469.

Sarewitz, D., 2004: How science makes environmental controversies worse. *Environmental Science & Policy*, **7**, 385-403.

Sarewitz, D., R. Pielke Jr., and R. Byerly Jr., 2000: *Prediction: Science, Decision Making, and the Future of Nature*. Island Press, Washington, DC, USA, 405 pp.

Scheffer, M., 2009: *Critical Transitions in Nature and Society*. Princeton University Press, Princeton, NJ, USA, 400 pp.

Schipper, L. and M. Pelling, 2006: Disaster risk, climate change and international development: scope for, and challenges to integration. *Disasters*, **30(1)**, 19-38.

Shaw, A., S. Sheppard, S. Burch, D. Flanders, A. Wiek, J. Carmichael, J. Robinson, and S. Cohen, 2009: Making local futures tangible – synthesizing, downscaling, and visualizing climate change scenarios for participatory capacity building. *Global Environmental Change*, **19(4)**, 447-463.

Shelby, R., D. Edmunds, A. James, J.A. Perez, Y. Shultz, and T. Angogino, 2012: Partnering with the Pinoleville Pomo Nation: co-design methodology case study for creating sustainable, culturally-inspired renewable energy systems and infrastructure. *Sustainability*, **4**, 794-818.

Sietz, D., M. Boschütza, and J.T.R. Klein, 2011: Mainstreaming climate adaptation into development assistance: rationale, institutional barriers and opportunities in Mozambique. *Environmental Science & Policy*, **14(4)**, 493-502.

Simões, A.F., D.C. Kligerman, E.L. La Rovere, M.R. Maroun, M. Barata, and M. Obermaier, 2010: Enhancing adaptive capacity to climate change: the case of smallholder farmers in the Brazilian semi-arid region. *Environmental Science & Policy*, **13(8)**, 801-808.

Simon, D., 2010: The challenges of global environmental change for urban Africa. *Urban Forum*, **21(3)**, 235-248.

Sissoko, K., H. van Keulen, J. Verhagen, V. Tekken, and A. Battaglini, 2011: Agriculture, livelihoods and climate change in the West African Sahel. *Regional Environmental Change*, **11(Suppl. 1)**, S119-S125.

Smith, J.B., J.M. Vogel, and J.E. Cromwell, 2009: An architecture for government action on adaptation to climate change. An editorial comment. *Climatic Change*, **95**, 53-61.

Smith, J.B., T. Dickinson, J. Donahue, I. Burton, E. Haites, R. Klein, and A. Patwardhan, 2013: Development and climate change adaptation funding: coordination and integration. In: *International Climate Finance* [Haites, E. (ed.)]. Routledge, New York, NY, USA, pp. 54-71.

Sovacool, B.K., A.L. D'Agostino, H. Meenawat, and A. Rawlani, 2012: Expert views of climate change adaptation in least developed Asia. *Journal of Environmental Management*, **97**, 78-88.

Staples, K., 2011: *Developing Adaptation to Climate Change in the East of England*. Research Report – July 2011, produced by Sustainability East for East of England Local Government Association (EELGA), Sustainability East, Cambridge, UK, 93 pp.

Stohlgren, T., J. Schnase, J. Morisette, N. Most, E. Sheffner, C. Hutchinson, S. Drake, W. Van Leeuwen, and V. Kaupp, 2005: *Invasive Species Forecasting System: A Decision Support Tool for the U.S. Geological Survey – FY 2005 Benchmarking Report*. Vol. 1.6, National Aeronautics and Space Administration (NASA) Applied Sciences Directorate at the John C. Stennis Space Center (SSC), Hancock County, MS, USA, 32 pp.

Storbjörk, S., 2007: Governing climate adaptation in the local arena: challenges of risk management and planning in Sweden. *Local Environment*, **12(5)**, 457-469.

Storbjörk, S., 2010: It takes more to get a ship to change course. Barriers for organisational learning and local climate adaptation in Sweden. *Journal of Environmental Policy and Planning*, **12(3)**, 235-254.

Storbjörk, S. and J. Hedrén, 2011: Institutional capacity-building for targeting sea level rise in the climate adaptation of Swedish coastal zone management. Lessons from Coastby. *Ocean and Coastal Management*, **54(3)**, 265-273.

Stren, R., 2008: International assistance for cities in low and middle-income countries. *Environment and Urbanization*, **20(2)**, 377-393.

Stringer, L., J. Dyer, M. Reed, A. Dougill, C. Twyman, and D. Mkwambisi, 2009: Adaptation to climate change, drought and desertification: local insights to enhance policy in southern Africa. *Environmental Science & Policy*, **12**, 748-765.

Stive, M.J.C., L.O. Fresco, P. Kabat, B.W.A.H. Parmet, and C.P. Veerman, 2011: How the Dutch plan to stay dry over the next century. *Proceedings of Institution of Civil Engineers*, **164**, 114-121.

Suarez, P. and J. Linnerooth-Bayer, 2011: *Insurance-Related Instruments for Disaster Risk Reduction*. Background Paper prepared for Chapter 5 of the Global Assessment Report on Disaster Risk Reduction 2011, The International Strategy for Disaster Reduction (ISDR) and International Institute for Applied Systems Analysis (IIASA), The United Nations Secretariat of the International Strategy for Disaster Reduction (UNISDR), Geneva, Switzerland, 55 pp., www.preventionweb.net/english/hyogo/gar/2011/en/bgdocs/Suarez_&_Linnerooth-Bayer_2011.pdf.

Surminski, S. and D. Oramas-Dorta, 2011: *Building Effective and Sustainable Risk Transfer Initiatives in Low- and Middle-Income Economies: What Can We Learn from Existing Insurance Schemes?* Policy Paper, Centre for Climate Change Economics and Policy (CCCEP) and the Grantham Research Institute on Climate Change and the Environment, London, UK, 28 pp.

Tan, J., Y. Zheng, G. Song, L.S. Kalkstein, A.J. Kalkstein, and X. Tang, 2007: Heat wave impacts on mortality in Shanghai, 1998 and 2003. *International Journal of Biometeorology*, **51(3)**, 193-200.

Tanner, T., T. Mitchell, E. Polack, and B. Guenther, 2009: *Urban Governance for Adaptation: Assessing Climate Change Resilience in Ten Asian Cities.* IDS Working Paper No. 315, University of Sussex, Brighton, UK, 47 pp.

Termeer, C., R. Biesbroek, and M. van den Brink, 2012: Institutions for adapting to climate change: comparing national adaptation strategies in Europe. *European Political Science*, **11(1)**, 41-53.

Tessa, B. and P. Kurukulasuriya, 2010: Technologies for climate change adaptation: emerging lessons from developing countries supported by UNDP. *Journal of International Affairs*, **64(1)**, 17-31.

Thomas, D.S.G. and C. Twyman, 2005: Equity and justice in climate change adaptation amongst natural-resource-dependent societies. *Global Environmental Change*, **15**, 115-124.

Thomas, D.S.G., C. Twyman, H. Osbahr, and B. Hewitson, 2007: Adaptation to climate change and variability: farmer responses to intra-seasonal precipitation trends in South Africa. *Climate Change*, **83(3)**, 301-322.

Tobey, J., P. Rubinoff, D. Robadue Jr., G. Riccia, R. Volk, J. Furlow, and G. Anderson, 2010: Practicing coastal adaptation to climate change: lessons from integrated coastal management. *Coastal Management*, **38(3)**, 317-335.

Tompkins, E. and H. Eakin, 2012: Managing private and public adaptation to climate change. *Global Environmental Change*, **22**, 3-11.

Tompkins, E.L., W.N. Adger, E. Boyd, S. Nicholson-Cole, K. Weatherhead, and A. Arnell, 2010: Observed adaptation to climate change: UK evidence of transition to a well-adapting society. *Global Environmental Change*, **20(4)**, 627-635.

Tribbia, J. and S. Moser, 2008: More than information: what coastal managers need to plan for climate change. *Environmental Science & Policy*, **11(4)**, 315-328.

Turnbull, M. and E. Turvill, 2012: *Análisis de la Capacidad de Participación y de la Vulnerabilidad. Guía Para Profesionales*. Un recurso de Oxfam para la reducción de riesgos y la adaptación al cambio climático, Oxfam, Oxford, UK, 49 pp.

Uittenbroek, C.J., L.B. Janssen-Jansen, and H.A.C. Runhaar, 2012: Mainstreaming climate adaptation in urban planning: overcoming barriers, seizing opportunities and evaluating the results in two Dutch case studies. *Regional Environmental Change*, **13(2)**, 399-411.

UK Environment Agency, 2012: *Managing Flood Risk through London and the Thames Estuary: TE2100 Plan*. London: Environment Agency, 226 pp.

UK HM Government, 2013: *The National Adaptation Programme: Making the Country Resilient to a Changing Climate*. The Stationery Office (TSO), London, UK, 182 pp.

Uljee, I., G. Engelen, and R. White, 1999: *Integral Assessment Module for Coastal Zone Management*. RamCo. 2.0 User Guide, Research Institute for Knowledge Systems (RIKS) Geo, Maastricht, Netherlands, 72 pp.

UNDP, 2004: *Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies, and Measures.* United Nations Development Programme (UNDP), Cambridge University Press, Cambridge, UK, 258 pp.

UNDP, 2010a: *Designing Climate Change Adaptation Initiatives: A UNDP Toolkit for Practitioners*. United Nations Development Programme (UNDP) Bureau of Development Policies, Environment and Energy Group, New York, NY, USA, 58 pp.

UNDP, 2010b: *Mapping Climate Change Vulnerability and Impact Scenarios: A Guidebook for Sub-National Planners*. United Nations Development Programme (UNDP) Bureau of Development Policies, Environment and Energy Group, New York, NY. USA, 83 pp.

UNECE, 2009: *Guidance on Water and Adaptation to Climate Change*. United Nations Economic Commission for Europe (UNECE), Convention on the Protection and Use of Transboundary Watercourses and International Lakes, UNECE, Geneva, Switzerland, 127 pp.

UNFCCC, 2007: *Investment and Financial Flows to Address Climate Change.* United Nations Framework Convention on Climate Change (UNFCCC) Secretariat, Bonn, Germany, 272 pp. unfccc.int/files/cooperation_and_support/financial_mechanism/application/pdf/background_paper.pdf.

UNFCCC, 2011: *Report on the Workshop to Identify Challenges and Gaps in the Implementation of Risk Management Approaches to the Adverse Effects of Climate Change*. FCCC/SBI/2011/INF.11, Subsidiary Body for Implementation, Thirty-fifth session, United Nations Framework Convention on Climate Change (UNFCCC) Secretariat, Bonn, Germany, 17 pp.

UNFCCC, 2012: *Technology Transfer Information Clearinghouse*. United Nations Framework Convention on Climate Change (UNFCCC) Secretariat, Bonn, Germany, unfccc.int/ttclear/pages/home.html.

UNFCCC, 2013: *Synthesis Report on the Implementation of the Framework for Capacity-Building in Developing Countries*. Subsidiary Body for Implementation, Thirty-eighth session, United Nations Framework Convention on Climate Change (UNFCCC) Secretariat, Bonn, Germany, 13 pp.

UN-HABITAT, 2010: *Climate Change Strategy 2010-2013*. United Nations Human Settlements Programme (UN-HABITAT), Nairobi, Kenya, 12 pp.

UN-HABITAT, 2011a: *Cities and Climate Change: Global Report on Human Settlements 2011*. United Nations Human Settlements Programme (UN-HABITAT), Nairobi, Kenya, 279 pp.

UN-HABITAT, 2011b: *Planning for Climate Change: A Strategic Values-Based Approach for Urban Planners*. Version 1: For Field Testing and Piloting in Training, United Nations Human Settlements Programme (UN-HABITAT), Urban Environmental Planning Branch, UN-HABITAT, Nairobi, Kenya, 197 pp.

UNISDR, 2006: *Global Survey of Early Warning Systems*. United Nations Inter-Agency Secretariat of the International Strategy for Disaster Reduction (UNISDR), Geneva, Switzerland and ISDR Platform for the Promotion of Early Warning (PPEW), Bonn, Germany, 46 pp.

Urwin, K. and A. Jordan, 2008: Does public policy support or undermine climate change adaptation? Exploring policy interplay across different scales of governance. *Global Environmental Change*, **18(1)**, 180-191.

USAID, 2007: *Adapting to Climate Variability and Change*: *A Guidance Manual for Development Planning*. United States International Development Agency (USAID), Washington, DC, USA, 24 pp.

Vammen Larsen, S., L. Kørnøv, and A. Wejs, 2012: Mind the gap in SEA: an institutional perspective on why assessment of synergies amongst climate change mitigation, adaptation and other policy areas are missing. *Environmental Impact Assessment Review*, **33**, 32-40.

Van Aalst, M.K., 2009: Chapter 3: Bridging timescales. In: *World Disasters Report 2009 – Focus on Early Warning, Early Action* [Knight, L. (ed.)]. International Federation of Red Cross and Red Crescent Societies (IFRC), Geneva, Switzerland, pp. 68-93.

Van Aalst, M.K., T. Cannon, and I. Burton, 2008: Community level adaptation to climate change: the potential role of participatory community risk assessment. *Global Environmental Change*, **18(1)**, 165-179.

Van den Berg, M. and F. Coenen, 2012: Integrating climate change adaptation into Dutch local policies and the role of contextual factors. *Local Environment*, **17(4)**, 441-460.

Van den Brink, M., C. Termeer, and S. Meijerink, 2011: Are Dutch water safety institutions prepared for climate change? *Journal of Water and Climate Change*, **2(4)**, 272-287.

Wade, S.D., J. Rance, and N. Reynard, 2013: The UK Climate Change Risk Assessment 2012: assessing the impacts on water resources to inform policy makers. *Water Resources Management*, **27(4)**, 1085-1109.

Wall, E. and K. Marzall, 2006: Adaptive capacity for climate change in Canadian rural communities. *Local Environment*, **11**, 373-397.

Warner, K., N. Ranger, S. Surminski, M. Arnold, J. Linnerooth-Bayer, E. Michel-Kerjan, P. Kovacs, and C. Herweijer, 2009: *Adaptation to Climate Change: Linking Disaster Risk Reduction and Insurance*. United Nations International Strategy for Disaster Reduction (UNISDR), Geneva, Switzerland, 18 pp.

West, C.C. and M.J. Gawith (eds.), 2005: *Measuring Progress: Preparing for Climate Change Through the UK Climate Impacts Programme*. UKCIP Technical Report, United Kingdom Climate Impacts Programme (UKCIP), School of Geography and the Environment, Oxford University Centre for the Environment (OUCE), Oxford, UK, 71 pp.

Westerhoff, L., C. Keskitalo, and S. Juhola, 2011: Capacities across scales: local to national adaptation policy in four European countries. *Environmental Science and Policy*, **14(3)**, 239-247.

Wilbanks, T.J. and R.W. Kates, 2010: Beyond adapting to climate change: embedding adaptation in responses to multiple threats and stresses. *Annals of the Association of American Geographers*, **100(4)**, 719-728.

Wilby, R.L. and R. Keenan, 2012: Adapting to flood risk under climate change. *Progress in Physical Geography*, **36**, 348-378.

Wilson, E., 2006: Adapting to climate change at the local level: the spatial response. *Local Environment*, **11(6)**, 609-625.

Wolf, J., N. Adger, I. Lorenzoni, L. Abrahamson, and R. Raine, 2010: Social capital, individual responses to heat waves and climate change adaptation: an empirical study of two UK cities. *Global Environmental Change*, **20**, 44-52.

Wolfram, S., 2002: *A New Kind of Science*. Wolfram Media, Inc., Champaign, IL, USA, 1197 pp.

World Bank, 2009: *Adapting to Climate Change in Europe and Central Asia*. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 116 pp.

World Bank, 2010: *World Development Report 2010: Development and Climate Change*. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 417 pp.

World Bank, 2011a: *Guide to Climate Change Adaptation in Cities*. Urban Development and Local Government Unit, Sustainable Development Network, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 100 pp.

World Bank, 2011b: *Private Activity in Infrastructure Remained at Peak Levels and Highly Selective in 2010*. PPI Data Update Note 55, Private Participation in Infrastructure (PPI) Database, The World Bank Group, Washington, DC, USA, 4 pp., ppi.worldbank.org/features/September-2011/2010-Global-update-note-final-08-31-2011.pdf.

World Bank Group, 2011: *Mobilizing Climate Finance*. Paper prepared at the request of the G20 Finance Ministers, Preparation coordinated by the World Bank Group, in close partnership with the IMF, the OECD and the Regional Development Banks (RDBs), The World Bank Group, Washington, DC, USA, 56 pp., www.imf.org/external/np/g20/pdf/110411c.pdf.

WUCA, 2010: *Decision Support Planning Methods: Incorporating Climate Change Uncertainties into Water Planning*. Water Utility Climate Alliance (WUCA), San Francisco, CA, USA, 102 pp.

Yang, X., E. Lin, S. Ma, H. Ju, L. Guo, W. Xiong, Y. Li, and Y. Xu, 2007: Adaptation of agriculture to warming in Northeast China. *Climatic Change*, **84**, 45-58.

Yohe, G.W., R.D. Lasco, Q.K. Ahmad, N.W. Arnell, S.J. Cohen, C. Hope, A.C. Janetos, and R.T. Perez, 2007: Perspectives on climate change and sustainability. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability*. *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. Van Der Linde, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 811-841.

Young, O.R., 2010: Institutional dynamics: resilience, vulnerability and adaptation in environmental and resource regimes. *Global Environmental Change*, **20(3)**, 378-385.

Zimmerman, R. and C. Faris, 2010: Infrastructure impacts and adaptation challenges. In: Climate change adaptation in New York City: building a risk management response: New York City Panel on Climate Change 2010 report [Rosenzweig C. and W. Solecki (eds.)]. *Annals of the New York Academy of Science*, **1196**, 63-85.

16 Adaptation Opportunities, Constraints, and Limits

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This chapter should be cited as:
Klein, R.J.T., G.F. Midgley, B.L. Preston, M. Alam, F.G.H. Berkhout, K. Dow, and M.R. Shaw, 2014: Adaptation opportunities, constraints, and limits. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 899-943.

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Executive Summary

Risk-based approaches to decision making provide a useful foundation for assessing the potential opportunities, constraints, and limits associated with adaptation of human and natural systems (*medium evidence*, *high agreement*). Risk management frames the consequences of climate change and potential adaptation responses in the context of actors' values, objectives, and planning horizons as they make decisions under uncertainty. Adaptation planning and implementation are therefore contingent on actors' perceptions of risk. Some risks may be routine and/or the consequences so minor that they are accepted. Other risks may be judged intolerable because they pose fundamental threats to actors' objectives or the sustainability of natural systems. A key objective of adaptation is to avoid such intolerable risks. Yet, the capacity of societal actors and natural systems to adapt is finite, and thus there are limits to adaptation. {16.2, 16.3.2, 16.4, Box 16-1}

Understanding of how the adaptive capacity of societal actors and natural systems influences the potential for adaptation to effectively manage climate risk has improved since the Fourth Assessment Report (AR4; *very high confidence*). Adaptive capacity is influenced by actors' abilities to capitalize on available opportunities that ease the planning and implementation of adaptation as well as constraints that make adaptation processes more difficult for both human and natural systems. Opportunities and constraints are unevenly distributed among global regions, communities, sectors, ecological systems, and species as well as across different time periods. Recent studies have provided greater recognition of the role of private businesses in facilitating adaptation. However, much of the current knowledge about adaptation opportunities and constraints is dominated by insights from public institutions and community-based case studies. {16.2-5, Box 16-1}

Opportunities exist to enable adaptation planning and implementation for actors across all sectors and geographic regions (*very high confidence*). Adaptation guidance, information, and tools are increasingly available to practitioners operating in different sectoral, regional, and organizational contexts. Enhancing the awareness of individuals, organizations, and institutions about climate change vulnerability, impacts, and adaptation can help build individual and institutional capacity for adaptation planning and implementation. However, addressing knowledge deficits alone is not sufficient to achieve successful adaptation. The development and provision of tools for risk and vulnerability assessment as well as decision-support tools and early warning systems can help actors prioritize adaptation needs and identify options that reduce vulnerability. Opportunities can also arise as actors learn from experience with climate variability and incorporate consideration for long-term climate change into disaster risk reduction efforts. Formal policies regarding infrastructure design standards or spatial planning can trigger adaptation action. However, many adaptation opportunities arise as ancillary benefits of actions implemented for reasons other than climate change. {16.2, 16.3.1, 16.5; Tables 16-1, 16-3; Boxes 16-1, 16-2, CC-EA}

A range of biophysical, institutional, financial, social, and cultural factors constrain the planning and implementation of adaptation options and potentially reduce their effectiveness (*very high confidence*). Adaptation of both human and natural systems is influenced by the rate of climate change as well as rates of economic development, demographic change, ecosystem alteration, and technological innovation. Adaptation planning and implementation may require significant inputs of knowledge as well as human, social, and financial capital. Real or perceived deficiencies in access to such resources can and do constrain adaptation efforts in both developing and developed nations. Public and private institutions influence the distribution of such resources as well as the development of policies, legal instruments, and other measures that facilitate adaptation. Therefore, institutional weaknesses, lack of coordinated governance, and conflicting objectives among different actors can constrain adaptation. Cultural characteristics including age, gender, and sense of place influence risk perception, entitlements to resources, and choices about adaptation. Societal actors and natural systems may experience multiple constraints that interact. {16.2, 16.3.2, 16.5; Tables 16-2, 16-3; Boxes 16-1, 16-3}

Limits to adaptation can emerge as a result of the interactions among climate change and biophysical and socioeconomic constraints (*medium evidence*, *high agreement*). An adaptation limit occurs owing to the inability to avoid an intolerable risk to an actor's objectives and/or to the sustainability of a natural system. Understanding of limits is informed by historical and recent experience where limits to adaptation have been observed, as well as by limits that are anticipated to arise as a consequence of future global change. Recent studies have provided valuable insights regarding global "tipping points," "key vulnerabilities," or "planetary boundaries" as well as evidence of climate thresholds for agricultural crops, species of fish, forest and coral reef communities, and humans. However, for most regions and sectors, there is a lack of empirical evidence to quantify magnitudes of climate change that would constitute a future adaptation limit. Furthermore, economic

development, technology, and cultural norms and values can change over time to enhance or reduce the capacity of systems to avoid limits. As a consequence, some limits may be considered "soft" in that they may be alleviated over time. Nevertheless, some limits may be "hard" in that there are no reasonable prospects for avoiding intolerable risks. Recent literature suggests that incremental adaptation may not be sufficient to avoid intolerable risks, and therefore transformational adaptation may be required to sustain some human and natural systems. {16.2-7; Table 16-3; Boxes 16-1, 16-4}

Greenhouse gas (GHG) mitigation can reduce the rate and magnitude of future climate change and therefore the likelihood that limits to adaptation will be exceeded (*medium evidence*, *high agreement*). Adaptation and GHG mitigation are complementary risk management strategies. However, residual loss and damage will occur from climate change despite adaptation and mitigation action. Knowledge about limits to adaptation can inform the level and timing of mitigation needed to avoid dangerous anthropogenic interference with the climate system. For example, the level of effort needed to adapt to a 4°C increase in global mean temperature would be significantly greater than that needed to adapt to lower magnitudes of temperature increase. Mitigation can reduce the likelihood of 4°C of warming and therefore the likelihood of exceeding limits to adaptation of natural and human systems. However, the empirical evidence needed to identify limits to adaptation of specific sectors, regions, ecosystems, or species that can be avoided with different GHG mitigation pathways is lacking. {16.3.2.2, 16.6; Box 16-3}

The selection and implementation of specific adaptation options has ethical implications (*very high confidence*). Adaptation decision making involves the reconciliation of legitimate differences about how adaptation resources are distributed and the values that adaptation seeks to protect. For example, the costs and benefits of different adaptation options, such as insurance schemes or large-scale infrastructure projects, may be inequitably distributed among different actors and stakeholders. Such inequities may generate ethical questions regarding who is advantaged or disadvantaged by adaptation actions. In addition, awareness that climate change may exceed the capacity of actors to adapt may have ethical implications for decisions regarding mitigation and climate targets as well as investments in GHG mitigation policies and measures. National and international law as well as decision making at regional and local scales among both public and private actors will influence distributive and procedural justice in adaptation planning and implementation. {16.3.3.8, 16.6-7; Table 16-4; Box 16-4}

Successful adaptation requires not only identifying adaptation options and assessing their costs and benefits, but also exploiting available mechanisms for expanding the adaptive capacity of human and natural systems (*medium evidence*, *high agreement*). Since the AR4, a growing body of literature provides guidance on how enabling conditions for adaptation can be developed and how constraints can be reduced. Continued development of this knowledge through research and practice could accelerate more widespread and successful adaptation outcomes. However, seizing opportunities, overcoming constraints, and avoiding limits can involve complex governance challenges and may necessitate new institutions and institutional arrangements to effectively address multi-actor, multiscale risks. {16.2-3, 16.5, 16.8; Table 16-1; Box CC-EA}

16.1. Introduction and Context

Since the IPCC's Fourth Assessment Report (AR4), demand for knowledge regarding the planning and implementation of adaptation as a strategy for climate risk management has increased significantly (Preston et al., 2011a; Park et al., 2012). This chapter assesses recent literature on the opportunities that create enabling conditions for adaptation as well as the ancillary benefits that may arise from adaptive responses. It also assesses the literature on biophysical and socioeconomic constraints on adaptation and the potential for such constraints to pose limits to adaptation. Given the available evidence of observed and anticipated limits to adaptation, the chapter also discusses the ethical implications of adaptation limits and the literature on system transformational adaptation as a response to adaptation limits.

To facilitate this assessment, this chapter provides an explicit framework for conceptualizing opportunities, constraints, and limits (Section 16.2). In this framework, the core concepts including definitions of adaptation, vulnerability, and adaptive capacity are consistent with those used previously in the AR4 (Adger et al., 2007). However, the material in this chapter should be considered in conjunction with that of complementary WGII AR5 chapters. These include Chapter 14 (Adaptation Needs and Options), Chapter 15 (Adaptation Planning and Implementation), and Chapter 17 (Economics of Adaptation). Material from other WGII AR5 chapters is also relevant to informing adaptation opportunities, constraints, and limits, particularly Chapter 2 (Foundations for Decision Making) and Chapter 19 (Emergent Risks and Key Vulnerabilities). This chapter also synthesizes relevant material from each of the sectoral and regional chapters (Section 16.5).

To enhance its policy relevance, this chapter takes as its entry point the perspective of actors as they consider adaptation response strategies over near, medium, and longer terms (Eisenack and Stecker, 2012; Dow et al., 2013a,b). Actors may be individuals, communities, organizations, corporations, non-governmental organizations (NGOs), governmental agencies, or other entities responding to real or perceived climate-related stresses or opportunities as they pursue their objectives (Patt and Schröter, 2008; Blennow and Persson, 2009; Frank et al., 2011). These actors may seek to navigate near-term constraints to implement adaptation while simultaneously working to alleviate those constraints to enable greater flexibility and adaptive capacity in the future. Therefore, it is necessary to consider diverse time frames for possible social, institutional, technological, and environmental changes. These time frames also differ in the types of uncertainties that are relevant, ranging from those of climate scenarios and models, possible system thresholds, nonlinear responses or irreversible changes in social or environmental systems, and the anticipated magnitude of impacts associated with higher or lower levels of climate change (Meze-Hausken, 2008; Hallegatte, 2009; Briske et al., 2010).

To provide further background and context, this chapter proceeds by revisiting relevant findings on adaptation opportunities, constraints, and limits within the AR4 and the more recent IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) (IPCC, 2012). The chapter then presents a framework for adaptation, opportunities, and limits with an emphasis on explicit definitions of these concepts to facilitate assessment. Key components of this framework are assessed in subsequent chapters, including the synthesis of how these components are treated among the different sectoral and regional chapters of the WGII AR5 report. The chapter subsequently assesses relationships between mitigation and adaptation opportunities, constraints, and limits as well as their ethical implications. The chapter concludes with discussion of key pathways forward for research and practice to seize opportunities, overcome constraints, and avoid limits.

16.1.1. Summary of Relevant AR4 Findings

The AR4 Summary for Policymakers of Working Group II concluded that there are "formidable environmental, economic, informational, social, attitudinal and behavioural barriers to the implementation of adaptation" and that "availability of resources and building adaptive capacity are particularly important" (IPCC, 2007a, p. 19). These findings were based primarily on Chapter 17, Assessment of Adaptation Practices, Options, Constraints and Capacity (Adger et al., 2007). The key conclusion from Adger et al. (2007, p. 719), as relevant to this chapter, was as follows: "There are substantial limits and barriers to adaptation (*very high confidence*)." The authors go on to discuss biophysical and technological limits to adaptation as well as barriers arising from technological, financial, cognitive and behavioral, and social and cultural factors. The authors also noted both significant knowledge gaps and impediments to the sharing of relevant information to alleviate those gaps.

These findings were further evidenced by the sectoral, and particularly regional, chapters of the WGII AR4 report. For example, the chapters assessing impacts and adaptation in Africa, Asia, and Latin America collectively emphasized the significant constraints on adaptation in developing nations. Meanwhile, the chapter on Small Islands by Mimura et al. (2007) identified several constraints to adaptation including limited natural resources and relative isolation. Finally, in the chapter on Polar Regions, Anisimov et al. (2007) noted that indigenous groups have developed resilience through sharing resources in kinship networks that link hunters with office workers, and even in the cash sector of the economy. However, they concluded that such responses may be constrained by social, cultural, economic, and political factors. For all of these regions, adaptation constraints are linked to governance systems and the quality of national institutions as well as limited scientific capacity and ongoing development challenges (e.g., poverty, literacy, and civil and political rights).

The AR4 also provided evidence that constraints on adaptation are not limited to the developing world. For example, Hennessy et al. (2007) reported that while adaptive capacity in Australia and New Zealand has strengthened over time, a number of constraints remain including access to tools and methods for impact assessment as well as appraisal and evaluation of adaptation options. They also note weak linkages among the various strata of government regarding adaptation policy and skepticism among some populations toward climate change science. For North America, Field et al. (2007) identify a range of social and cultural barriers, informational and technological barriers, and financial and market barriers. The chapter on Europe mentions the limits faced by species and ecosystems due to lack of migration space, low soil fertility, and human alterations of the landscape (Alcamo et al., 2007).

Several other AR4 chapters assessed literature relevant to this chapter. Chapter 18, Inter-Relationships between Adaptation and Mitigation (Klein et al., 2007), discussed the possible effect of mitigation on adaptation (an issue also considered by WGIII AR4, in particular by Fisher et al. (2007) and Sathaye et al. (2007)). Finally, Chapter 19, Assessing Key Vulnerabilities and the Risk from Climate Change (Schneider et al., 2007), outlined how the presence of adaptation constraints and limits is a contributing factor to vulnerability. Chapters that address similar themes also appear in the AR5, and cross-references are provided in this chapter to this more recent material.

16.1.2. Summary of Relevant SREX Findings

The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) assesses a broad array of literature on climate change, extreme events, adaptation, and disaster risk reduction. A central framing concept for the SREX was the assertion that (Lavell et al., 2012, p. 37), " . .while there is a long-standing awareness of the role of development policy and practice in shaping disaster risk, advances in the reduction of the underlying causes – the social, political, economic, and environmental drivers of disaster risk – remain insufficient to reduce hazard, exposure, and vulnerability in many regions (UNISDR, 2009, 2011) (*high confidence*)."

This summary of relevant SREX material focuses on how the key findings of the SREX provide insights relevant to the treatment of opportunities, constraints, and limits in this chapter.

With respect to opportunities, the linkages between development and disaster risk reduction provide a number of avenues for enhancing societal resilience to natural disasters and climate change. For example, the SREX highlights the benefits of considering disaster risk in national development planning if strategies to adapt to climate change are adopted (Lal et al., 2012). The observed dependence of disasters on underlying patterns of development is indicative of the opportunities for increasing societal resilience through sustainable development. In addition, incorporating adaptation into multi-hazard risk management may be an effective strategy for the efficient integrated management of natural hazards and future climate risk (O'Brien et al., 2012).

The SREX report also discussed the constraints associated with enhancing disaster risk reduction and climate adaptation. In particular, ongoing development deficits as well as inequality in coping and adaptive capacities pose fundamental constraints (Cardona et al., 2012). The SREX noted that national systems and institutions are critical for generating the capacity needed to manage the risks associated with climate variability and change (Lal et al., 2012). Yet capacity at one level of governance does not necessarily convey capacity to other levels (Burton et al., 2012). Even in the presence of robust institutions, rates of socioeconomic and climate change can interact to constrain adaptation. For example, O'Brien et al. (2012) note that rapid socioeconomic development in vulnerable urban areas can increase societal exposure to natural hazards while simultaneously constraining the capacity of actors to implement policies and measures to reduce vulnerability. Overcoming these constraints to achieve development objectives is constrained by a paucity of disaster data at the local level as well as persistent uncertainties regarding the manifestation of extreme events in future decades (Cutter et al., 2012; Seneviratne et al., 2012).

The SREX report cautioned that natural hazards, climate change, and societal vulnerability can pose fundamental limits to sustainable development. Such limits can arise from the exceedance of natural and/or societal thresholds or tipping points (Lal et al., 2012; O'Brien et al., 2012; Seneviratne et al., 2012). Accordingly, the SREX concludes that adaptation options should include not only incremental adjustments to climate variability and climate change, but also transformational changes that alter the fundamental attributes of systems. Though challenging to implement, such transformation may be aided by actors questioning prevailing assumptions, paradigms, and management objectives toward the development of new ways of managing risk and identifying opportunities (O'Brien et al., 2012).

16.2. A Risk-Based Framework for Assessing Adaptation Opportunities, Constraints, and Limits

Risk is an intrinsic element of any understanding of "*dangerous anthropogenic interference with the climate system*" (UNFCCC, 1992) and associated assumptions about the capacity of human and natural systems to adapt to climatic change. The United Nations Framework Convention on Climate Change (UNFCCC) refers specifically to adaptation of ecosystems, threats to food production, and sustainable economic development. While there is evidence of opportunities in natural and human systems to adapt to climate changes, there is also evidence that the potential to adapt is constrained, or more difficult, in some situations, and faces limits in others (*very high confidence*; e.g., Adger et al., 2009; Dow et al., 2013a,b; see also Sections 16.3-5).

This chapter applies a risk-based framework and a set of linked definitions to the assessment of adaptation opportunities, constraints, and limits. This approach is consistent with other risk management approaches to guiding adaptation responses to climate change (IPCC, 2012; see also Sections 1.3.4, 2.1.2, 14.4, 15.3). The adaptation literature ascribes a number of different meanings to the terms opportunities, constraints, and limits, which may have added confusion to an important scientific and policy debate. The AR4, for example, provided a specific definition of adaptation limits, but used the terms barriers and constraints interchangeably to describe general impediments to adaptation (Adger et al., 2007). Similar ambiguities are apparent within the rapidly expanding literature focused on adaptation constraints (Biesbroek et al., 2013a).

The framework and definitions employed here draw on a number of literatures (Dow et al., 2013a,b), in particular vulnerability assessment (Füssel, 2006; Füssel and Klein, 2006) and risk assessment (Jones, 2001; Klinke and Renn, 2002; Renn, 2008; National Research Council, 2010) as well as climate adaptation (Hulme et al., 2007; Adger et al., 2009; Hall et al., 2012). Moving from such general definitions to applications requires specifying who or what is adapting, what they are adapting to, and the process of adaptation (Smit et al., 1999). Hence, this chapter explores adaptation opportunities, constraints, and limits from the context of social actors, which includes individuals, businesses, government agencies, or informal social groups.

Frequently Asked Questions

FAQ 16.1 | What is the difference between an adaptation barrier, constraint, obstacle, and limit?

An adaptation constraint represents a factor or process that makes adaptation planning and implementation more difficult. This could include reductions in the range of adaptation options that can be implemented, increases in the costs of implementation, or reduced efficacy of selected options with respect to achieving adaptation objectives. In this context, a constraint is synonymous with the terms adaptation barrier or obstacle that also appear in the adaptation literature. However, the existence of a constraint alone does not mean that adaptation is not possible or that one's objectives cannot be achieved. In contrast, an adaptation limit is more restrictive in that it means there are no adaptation options that can be implemented over a given time horizon to achieve one or more management objectives, maintain values, or sustain natural systems. This implies that certain objectives, practices, or livelihoods as well as natural systems may not be sustainable in a changing climate, resulting in deliberate or involuntary system transformations.

An explicit focus on risk is particularly useful to understanding climate adaptation (Jones and Preston, 2011; Dow et al., 2012b). Adaptation is intended to reduce the risk to assets or systems of value (Adger et al., 2012b). The concept of risk integrates the dimensions of probability and uncertainty with the material and normative dimensions that shape societal responses to threats (Renn, 2008). Figure 16-1 relates judgments about risk and the ability to maintain risks at a tolerable level to the concept of adaptation and adaptation opportunities, constraints, and limits (Box 16-1). Drawing on the work of Klinke and Renn (2002), actors evaluate risks based on one of three categories: acceptable, tolerable, and intolerable. Acceptable risks are those deemed so low that additional efforts at risk reduction, in this case climate adaptation efforts, are not justified. Tolerable risks relate to situations where adaptive risk management efforts are required and effective for risks to be kept within reasonable levels. The scope of risks that fall within the tolerable area is influenced by adaptation opportunities and constraints. Therefore, the categorization of risks varies across spatial, jurisdictional, and temporal. As discussed later in this chapter, opportunities and constraints may be physical, technological, economic, institutional, legal, cultural, or environmental in nature (Sections 16.3, 16.5-7). Constraints may limit the range of available adaptation options creating the potential for residual damages for actors, species, or ecosystems associated with specific regions or sectors. Under some circumstances, the risk of residual damage may be viewed as an acceptable or tolerable trade-off (Stern et al., 2006; de Bruin et al., 2009a).

Intolerable risks may be related to threats to core social objectives associated with health, welfare, security, or sustainability (Klinke and Renn, 2002; Renn, 2008; Dow et al., 2013a,b). Risks become intolerable when practicable or affordable adaptation options to avoid escalating risks to such valued objectives or biophysical needs become unavailable. Therefore, a limit is a point when an intolerable risk must be accepted; the objective itself must be relinquished; or some adaptive transformation must take place to avoid intolerable risk. Such a discontinuity may take several forms such as individual's decision to relocate, an insurance company's decision to withdraw coverage, or a species' extinction. The alternative to such discontinuities is an escalating and unmediated risk of losses (Moser and Ekstrom, 2010; see also Section 16.4.2). While individuals have their own perspectives about what are acceptable, tolerable, or intolerable risks, collective judgments about risk are also codified through mechanisms such as engineering design standards, air and water quality standards, and legislation that establishes goals for regulatory action. There are also international agreements that establish norms and rights relevant to climate change risks (Knox, 2009; OHCHR, 2009; Crowley, 2011), such as the Universal Declaration of Human Rights, the International Covenant on Civil and Political Rights, and the International Covenant on Economic, Social and Cultural Rights. Further, these high level responses often shape the constraints and opportunities to adaptation and responses to risk at lower levels through the distribution

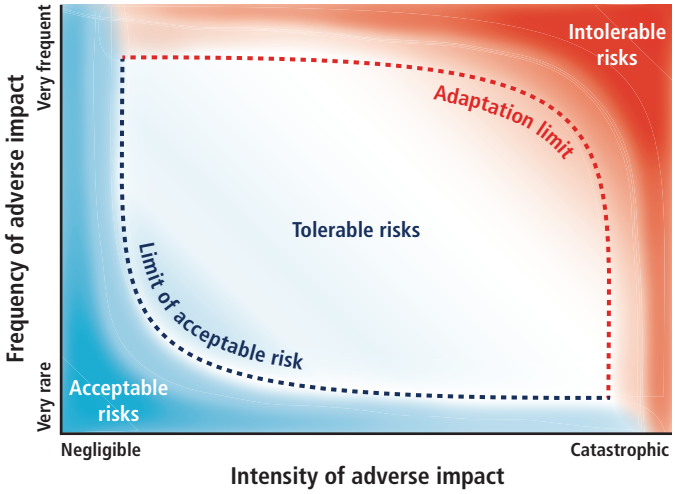

Figure 16-1 | Conceptual model of the determinants of acceptable, tolerable, and intolerable risks and their implications for limits to adaptation (Dow et al., 2013b, based on Klinke and Renn, 2002; see also Renn and Klinke, 2013). In this conceptual diagram, adaptation efforts are seen as keeping risks to objectives within the tolerable risk space. Opportunities and constraints influence the capacity of actors to maintain risks within a tolerable range. The dotted lines indicate that individual or collective views on risk tolerance with respect to the frequency and intensity of climate-related risks are not fixed, but may vary and change over time. In addition, the shape or angle of the lines and the relative area in each section of the diagram are illustrative and may themselves change as capacities and attitudes change. The shaded areas represent the potential differences in perspective among actors.

Box 16-1 | Definitions of Adaptation Opportunities, Constraints, and Limits

Adaptation Opportunities: *Factors that make it easier to plan and implement adaptation actions, that expand adaptation options, or that provide ancillary co-benefits*. These factors enhance the ability of an actor(s) to secure their existing objectives, or for a natural system to retain productivity or functioning. For instance, increased public awareness and support for adaptation, availability of additional resources from actors at other levels of governance to overcome constraints and soft limits, and interest in acquiring co-benefits arising from adaptation strategies can all facilitate adaptation planning and implementation. Private sector efforts in research and development that can improve affordability, flexibility, or ease of implementation could also create opportunities (Section 14.2.4). Such adaptation opportunities, sometimes also referred to as adaptation enablers, are distinct from opportunities arising from climate change (e.g., longer growing seasons), which are commonly referred to as potential benefits of climate change or adaptation options.

Adaptation Constraints: *Factors that make it harder to plan and implement adaptation actions*. Adaptation constraints restrict the variety and effectiveness of options for actors to secure their existing objectives, or for a natural system to change in ways that maintain productivity or functioning. These constraints commonly include lack of resources (e.g., funding, technology, or knowledge) (Section 16.3.2), institutional characteristics that impede action (Section 16.3.2.8), or lack of connectivity and environmental quality for ecosystems (Section 4.4). The terms "barriers" and "obstacles" are frequently used as synonyms. Constraints—alone or in combination—can drive an actor or natural system to an adaptation limit.

Adaptation Limit: *The point at which an actor's objectives or system's needs cannot be secured from intolerable risks through adaptive actions* (Adger et al., 2009; Moser and Ekstrom, 2010; Dow et al., 2013a,b; Islam et al., 2014).

Hard Adaptation Limit: No adaptive actions are possible to avoid intolerable risks.
Soft Adaptation Limit: Options are currently not available to avoid intolerable risks through adaptive action.

A limit to adaptation means that, for a particular actor, system, and planning horizon of interest, no adaptation options exist, or an unacceptable measure of adaptive effort is required, to maintain societal objectives or the sustainability of a natural system. Objectives include, for example, maintaining safety standards such as those codified in laws, regulations, or engineering design standards (e.g., 1-in-500 year levees); security of air or water quality; as well as equity, cultural cohesion, and preservation of livelihoods. Requirements for sustaining natural systems might include temperature ranges or moisture availability. In the case of hard limits, no adaptation options are foreseeable, even when looking beyond the current planning horizon. For soft limits, however, adaptation options could become available in the future owing to changing attitudes or values or as a result of innovation or other resources becoming available to an actor. For example, 31 Native Alaskan villages are facing "imminent threats" due to coastal erosion and at least 12 of the 31 have begun to explore relocation or have decided to partially or totally relocate (US GAO, 2009). In the case of these communities with minimum local revenue, the ability to relocate depends on the political and financial support of the U.S. federal government (Huntingon et al., 2012). Therefore, limits are strongly influenced by relationships among public and private actors and institutions across different spatial, temporal, and jurisdictional scales (Cash et al., 2006; see also Section 16.4.1).

of resources, institutional design, and support of capacity development (Sections 16.2-3, 16.4.1). If these risks and discontinuities have global-scale consequences, they can be linked to "key vulnerabilities" to climate change (Section 19.6). Consistent with our framing of adaptation limits, such key vulnerabilities would need to be assessed in terms of the limits they imply for specific social actors, species, and ecosystems.

It is essential to evaluate opportunities, constraints, and limits with respect to both the rate and magnitude of climate change and the relevant time horizon for an actor, a species, or an ecosystem. Opportunities, constraints, and limits to adaptation develop along a dynamic continuum (i.e., the dotted lines in Figure 16-1 can shift), together conditioning the capacity of natural and human systems to adapt to climate change. New opportunities for adaptation may emerge through time; constraints may be loosened; and some, although not all, limits that arise in the present may eventually be shifted or removed altogether. For a given social actor, the time horizon for adaptation decisions usefully bounds an analysis of opportunities, constraints, and limits. For natural systems,

the rate of species responses relative to changes in environmental conditions is a limit to the capacity to adapt (Sections 4.3.2.5, 4.4, 16.3.2.3, 16.4.1). The observed rate of evolutionary and other species responses ranges from rapid to inadequate to allow persistence (Hoffmann and Sgro, 2011).

Because adaptation limits relate to adaptation resources and attitudes to risk that may change over time, some limits may be viewed as "soft" or time sensitive (Section 16.4.1). While a given adaptation option may not be available today or require impracticable levels of effort, it may become available through innovation or changes in attitudes in time. Soft limits may be shifted by investments in research and development, changes in regulatory rules or funding arrangements, or by changing social or political attitudes (Park et al., 2012; Adger et al., 2013). Other limits are "hard" or time insensitive in that there is no known process to change them (Section 16.4.1). Examples of hard limits include water supply in fossil aquifers, limits to retreat on islands, and loss of genetic diversity.

16.3. Adaptation Opportunities and Constraints

Different actors, sectors, and geographic regions have differential capacities to adapt to climate variability and change (*very high confidence*; Adger et al., 2007; IPCC, 2012), although those capacities can be difficult to measure (Tol et al., 2008; Hinkel, 2011). Since the AR4 (Adger et al., 2007), the literature on the factors that contribute to adaptive capacity has deepened (Adger et al., 2009; Moser and Ekstrom, 2010). This literature has evolved along two different pathways. One focuses on the range of opportunities that exist to facilitate adaptation planning and implementation. The other, which is also more extensive, focuses on describing the constraints that inhibit adaptation. Although they are sometimes treated in the literature as distinct, opportunities and constraints are complementary in that adaptive capacity is influenced jointly by the extent to which actors take advantage of available opportunities to pursue adaptation responses and the extent to which those actors or natural, unmanaged systems experience constraints. In addition, factors that are identified as constraints may also reveal valuable opportunities for adaptation interventions to build adaptive capacity.

While some level of generalization regarding opportunities and constraints that are common to different regions, sectors, communities, and actors is possible, the manner in which they manifest is context dependent (*very high confidence*; Adger et al., 2007; Orlove, 2009; Kasperson and Berberian, 2011; Weichselgartner and Breviere, 2011; IPCC, 2012). For example, actors that frame adaptation as a process of capacity building or sustainable development may pursue different adaptation options with different opportunities and constraints compared with those that frame adaptation as largely addressing climate change impacts (McGray et al., 2007; Fünfgeld and McEvoy, 2011). Adaptation researchers apply their own frameworks and heuristics that influence understanding of adaptation processes (Biesbroek et al., 2013b; Preston et al., 2013b). Therefore, one must be cautious in applying generic assumptions regarding adaptation opportunities and constraints in assessments of vulnerability and adaptive capacity or in the identification of appropriate adaptation responses (Adger and Barnett, 2009; Barnett and Campbell, 2009; Mortreux and Barnett, 2009). The recent adaptation literature suggests significant work remains in understanding such context-specific determinants of vulnerability and adaptive capacity and in effectively using the knowledge gained from available case studies to facilitate adaptation more broadly (Tol and Yohe, 2007; Klein, 2009; Smith et al., 2010; Hinkel, 2011; Preston et al., 2011b; Biesbroek et al., 2013a). Therefore, the discussion of opportunities and constraints here should be considered in the context of the sectoral and regional synthesis (Section 16.5) as well as the sector- and region-specific material on constraints and opportunities in other WGII AR5 chapters.

16.3.1. Adaptation Opportunities

16.3.1.1. Enabling Conditions for Adaptation

Adaptation opportunities represent enabling factors that enhance the potential for actors to plan and implement actions to achieve their

Frequently Asked Questions

FAQ 16.2 | What opportunities are available to facilitate adaptation?

Although an extensive literature now exists regarding factors that can constrain adaptation, there is *very high confidence* that a broad range of opportunities exist for actors in different regions and sectors that can ease adaptation planning and implementation. Generally, sustainable economic development is an overarching process that can facilitate adaptation, and therefore represents a key opportunity to reduce adaptation constraints and limits. More specifically, those actions or processes that enhance the awareness of adaptation actors and relevant stakeholders and/or enhance their entitlements to resources can expand the range of adaptation options that can be implemented and help overcome constraints. The development and application of tools to support assessment, planning, and implementation can aid actors in weighing different options and their costs and benefits. Policies, whether formal policies of government institutions, initiatives of informal actors, or corporate policies and standards, can direct resources to adaptation and/or reduce vulnerability to current and future climate. Finally, the ability for humans to learn from experience and to develop new practices and technologies through innovation can significantly expand adaptive capacity in the future.

Table 16-1 | Identification of key adaptation opportunities. Each type of opportunity is represented by multiple illustrative examples as well as supporting references.

Opportunity	Examples	References
Awareness raising	Positive stakeholder engagement	O'Neill and Chicholson-Cole (2009); Kahan (2010)
	Communication of risk and uncertainty	Berry et al. (2011); Pidgeon and FIschhoff (2011); Pidgeon (2012); Lieske et al. (2013)
	Participatory research	Pearce et al. (2009); McNamara and McNamara (2011); Sheppard et al. (2011); Duru et al. (2012); Faysse et al. (2012)
Capacity building	Research, data, education, and training	PCAST (2011); WMO (2011); Bangay and Blum (2012); Lemos et al. (2013)
	Extensions services for agriculture	Deressa et al. (2009); Fosu-Mensah et al. (2012)
	Resource provision	Ayers (2009); Ayers and Huq (2009); Grasso (2010); Klein (2010); Rübbelke (2011)
	Development of human capital	Bowen et al. (2012); Lemos et al. (2013)
	Development of social capital	Deressa et al. (2009); Adger et al. (2010); Engle and Lemos (2010); Huang et al. (2011)
Tools	Risk analysis	van Aalst et al. (2008); Pidgeon and Butler (2009); Chin et al. (2010); Zhou et al. (2012); Wade et al. (2013)
	Vulnerability assessment	Allison et al. (2009); Moreno and Becken (2009); Nelson et al. (2010b); Romieu et al. (2010); Koh (2011); Preston et al. (2011b)
	Multi-criteria analysis	de Bruin et al. (2009b); Garfi et al. (2011); Yang et al. (2012); Kyung-Soo et al. (2013)
	Cost/benefit analysis	Tol et al. (2008); Hallegatte (2009); Weitzman (2009); Mechler and Islam (2013)
	Decision support systems	Norman et al. (2010); Wenkel et al. (2013)
	Early warning systems	Lowe et al. (2011); Lenton (2013); Marvin et al. (2013)
Policy	Integrated resource and infrastructure planning	Rosenberg et al. (2010); Becker et al. (2012); Heeres et al. (2012)
	Spatial planning	Brown (2011); Wheeler (2012); Pinto et al. (2013)
	Design/planning standards	Hamin and Gurran (2009); Mailhot and Duchesn (2009); Kwok and Rajkovich (2010); Ren et al. (2011); Nassopoulos et al. (2012)
Learning	Experience with climate vulnerability and disaster risk	Fiksel (2006); Crespo Cuaresma et al. (2008); Cutter et al. (2012)
	Learning-by-doing	Berkhout et al. (2006); Bulkeley and Castán Broto (2012); Roberts et al. (2012)
	Monitoring and evaluation	GIZ (2011a,b); Preston et al. (2011a); Adaptation Sub-Committee (2012)
Innovation	Technological change	Hanjra and Qureshi (2010); Chhetri et al. (2012); Lybbert and Sumner (2012); Rodima-Taylor et al. (2012); Vermeulen et al. (2012)
	Infrastructure efficiencies	Beard et al. (2009); Newton (2013)
	Digital/mobile telecommunications	Ospina and Heeks (2010a,b); Meera et al. (2012)

adaptation objective(s) or facilitate adaptive responses by natural systems to climate risk (Box 16-1). Therefore, an opportunity is distinct from an adaptation option, which is a specific means of achieving an adaptation objective (such as an early warning system as a means of reducing vulnerability to tropical cyclones) or a strategy for the conservation of an ecological system (Section 14.3; Table 14-1). Adaptation opportunities described here also do not consider the potential beneficial consequences of climate change (Box 16-1), an issue addressed to varying degrees among the various sectoral and regional chapters.

Opportunities for adaptation range from increasing awareness of climate change, its consequences, and the potential costs and benefits of adaptation options to the implementation of specific policies that create conditions that are conducive to adaptation implementation. For example, rice is a key food crop, particularly in Asia, in which 90% of rice is produced and subsequently consumed (Timmer, 2010). Multiple studies have identified rice as being particularly vulnerable to the effects of climate change, including both temperature and water availability impacts (Papademetriou et al., 2000). Therefore, planning and implementation of adaptive responses will be an important component of managing the risk of climate change to rice production (Howden et al., 2007; Lobell et al., 2008; Tilman et al., 2011; Anwar et al., 2013). A range of opportunities are available to support adaptation (Tables 16-1, 16-3) (*very high confidence*). Hypothetically, these could include the use of analysis tools to better understand vulnerabilities and thresholds in rice and develop scenarios of future consequences. That information could then be communicated to farmers, national governments, and international agencies to increase awareness of potential risks. Policies can be used to incentivize adaptation including investments in biotechnology research to breed more resistant strains as well as field studies to identify potential new regions that might be appropriate for rice cultivation in the future.

Such opportunities exist for other agricultural commodities as well as other sectors and regions at risk from climate change (Box 16-2). For example, there is growing recognition of the potential for using disaster response and recovery processes as a means of increasing resilience to future extreme events (Lavell et al., 2012). Meanwhile, case studies of Australian local governments as well as Inuit communities in the Arctic have identified a range of opportunities for building adaptive capacity and overcoming constraints (Smith et al., 2008; Ford, 2009; Ford et al., 2010). These include risk assessment, partnerships, establishment of monitoring and evaluation frameworks, developing finance mechanisms, and formal adaptation policy development.

Sustainable economic development is a critical foundation for the creation of adaptation opportunities (Sections 20.2, 20.6), because it has the potential to build the capacity of individuals and organizations to adapt (*very high confidence*). Sustainable development is associated with increasing opportunities for research, training, and education as

Box 16-2 | A Case Study of Opportunities for Adaptation and Disaster Risk Reduction

Bangladesh has been identified as a region of South Asia that is particularly vulnerable to tropical cyclones (Ali, 1999; Mallick and Rahman, 2013), and this vulnerability is projected to increase due to climate change (Karim and Mimura, 2008; Dasgupta et al., 2010). The nation's response to this vulnerability illustrates the manner in which multiple opportunities can converge to facilitate adaptation and disaster risk reduction. The Cyclone Preparedness Program (CPP) was launched in the 1960s to establish a warning system in coastal regions (Habib et al., 2012). The CPP has been continually improved in subsequent years with assistance from the International Federation of Red Cross and Red Crescent Societies and the International Foundation (Mallick and Rahman, 2013). A coastal reforestation program was also established in the 1960s to enhance natural buffers to storm surge (Mallick and Rahman, 2013; Box CC-EA). The Bangladesh Government initiated construction of cyclone shelters in the late 1980s, yet a cyclone in 1991 revealed that too few shelters were available (Bern et al., 1991; Chowdhury et al., 1993). This prompted collaboration between the government of Bangladesh, the United Nations Development Programme, and the World Bank to launch the Multipurpose Cyclone Shelter Program. That program characterized shelter needs along the coast and provided resources for their construction. In addition, shelter construction, which was concentrated around primary and secondary schools, coincided with national legislation requiring compulsory attendance in primary school, which required the construction of new schools. This created the opportunity for multi-purpose construction of buildings, reflecting the potential ancillary benefits that can arise from integrated planning (Section 16.3.1.2).

More recently, Bangladesh has begun to focus on increasing the resilience of the built environment. This effort has focused on the development of disaster-resilient habitat (Mallick and Rahman, 2007), where communities participate in the design and construction of resilient housing with support from international donors (Mallick et al., 2008; Mallick and Rahman, 2013). This may be a more cost-effective strategy for both reducing mortality and property damage (Mallick et al., 2008). The observed progress in reducing vulnerability to tropical cyclones is a function of various opportunities (awareness, assessment, policies, innovation, and capacity building) that have emerged over the past several decades that created conditions that enabled the implementation of specific policies, projects, and programs. Nevertheless, the additional risk posed by future climate change may necessitate further future investments (Dasgupta et al., 2010).

well as for enhancing access to expertise and tools for assessment activities and decision support. It also increases access to technologies that can enhance efficiencies. For example, water use in the USA has remained relatively constant since the mid-1980s, despite population growth, increases in agricultural yields, and expansion of electricity generation (Kenny et al., 2009). Improvements in technology and management practice stimulated by innovation, education, and learning have increased water use efficiency. This phenomenon may increase the resilience of U.S. water resources to climate change. Yet, these advances are a function of broader national and regional economic development trends. Therefore, future development pathways may have a significant influence on the opportunities for adaptation and therefore the adaptive capacity of adaptation actors (Sections 16.3.2.10, 20.6; Box 16-3).

16.3.1.2. Ancillary Benefits of Adaptation

Some adaptation options may offer ancillary benefits (or co-benefits) independent of their direct benefits with respect to reducing vulnerability to climate change (*very high confidence*; Section 17.2.3). The potential for ancillary benefits has two important implications for adaptation planning and implementation. First, their consideration may result in a more favorable assessment of the cost-effectiveness of a specific adaptation option (Hallegatte, 2009). Second, consideration of the ancillary benefits of adaptation may help in efficiently integrating adaptation into existing management and decision-making processes (Ahmed and Fajber, 2009; Dovers, 2010).

Such ancillary benefits may arise from adaptation responses in three ways:

- *Stimulating adaptation to current climate variability*: Although it is generally assumed that physical, ecological, and social systems are well adapted to current climatic conditions, this is frequently not the case (Dugmore et al., 2009; Heyd and Brooks, 2009). Increased awareness of the potential impacts of future climate change may, in some instances, lead to the implementation of adaptation options to reduce vulnerability or capitalize on opportunities (*medium evidence*, *high agreement*; Section 16.3.2.1).These options may have near-term ancillary benefits with respect to reducing vulnerability to current climate variability and extreme weather events (Füssel, 2008; Hallegatte, 2009; Ford et al., 2010). On the other hand, future reductions in vulnerability to climate change can be perceived as

ancillary benefits of near-term responses to current climate variability and natural disasters (Ziervogel et al., 2010a,b). Hence, there may be some ambiguity with respect to what actors perceive as the primary versus ancillary benefit of a particular policy or measure.

- *Generation of climate adaptation goods and services*: Adaptation planning and implementation often may require additional knowledge and investment of resources. Adaptation therefore represents a potential economic opportunity for producers of goods and services used to satisfy adaptation needs (*limited evidence*, *medium agreement*; EBI, 2013). Such services range from vulnerability assessment and risk analysis to the implementation of technology and engineering solutions. The Stern Review indicated that the market opportunities for new infrastructure and buildings resilient to climate change in Organisation for Economic Co-operation and Development (OECD) countries could be quite significant (Stern et al., 2006). For example, the market for snow machines will be influenced by growing concerns about snow cover in more marginal ski resorts (Scott et al., 2006). Higher elevation regions may see new opportunities as a result of snow resort shifts (Bark et al., 2010). Likewise, increased risks associated with track buckling caused by higher summer temperatures may trigger innovation and investment in new railway track and drainage systems (Bark et al., 2010). Rising damage caused by climate change could provide new markets for innovative insurance products and other risk-based financial services (*limited evidence*, *medium agreement*; Botzen et al., 2009, 2010). However, these ancillary benefits must be weighed against the adverse impacts that create the market for such services.
- *Advancing sustainable development*: As part of a larger portfolio of policies and measures, adaptation can assist in addressing existing development deficits while also meeting long-term sustainable development objectives (*very high confidence*; Sections 20.2, 20.6). For example, policy options related to management of water and natural resources under a changing climate; the development of water, transportation, and communication infrastructure; and the promotion of credit and insurance services can promote economic development, increase adaptive capacity, and reduce the impacts of climate change on the poor (Hertel and Rosch, 2010). Therefore, effective adaptation and climate risk management may be important enablers of sustainable economic development.

16.3.2. Adaptation Constraints

As discussed in the AR4 (Adger et al., 2007), a number of factors constrain planning and implementation of adaptation options (*very high confidence*). More recent studies have documented an expanded range of constraints in a diverse array of contexts, but Biesbroek et al. (2013a) note that there is no consensus definition of constraints or a consistent framework for their assessment. Although constraints are often discussed in the literature as discrete determinants of adaptive capacity, they rarely act in isolation (Dryden-Cripton et al., 2007; Smith et al., 2008; Moser and Ekstrom, 2010; Shen et al., 2011). Rather actors are challenged to navigate multiple, interacting constraints in order to achieve a given adaptation objective (*very high confidence*; Adger et al., 2007, 2009; Dryden-Cripton et al., 2007; Shen et al., 2008, 2011; Smith et al., 2008; Jantarasami et al., 2010; Moser and Ekstrom, 2010; see also Section 16.3.2.10). Multiple constraints can significantly reduce the range of adaptation options and opportunities available to actors and therefore may pose fundamental limits to adaptation (*very high confidence*; Section 16.4) and/or drive actors toward responses that may be maladaptive (*limited evidence*, *medium agreement*; Barnett and O'Neill, 2010; Eriksen et al., 2011).

16.3.2.1. Knowledge, Awareness, and Technology Constraints

The AR4 concluded that there are significant knowledge gaps and impediments to flows of information that can constrain adaptation, but knowledge in itself is not sufficient to drive adaptive responses (Adger et al., 2007). These conclusions are echoed by more recent literature. Adaptation practitioners and stakeholders in both developed (Tribbia and Moser, 2008; Gardner et al., 2010; Jantarasami et al., 2010; Ford et al., 2011; Milfont, 2012) and developing nations (Bryan et al., 2009; Deressa et al., 2009; Begum and Pereira, 2013; Pasquini et al., 2013) continue to identify knowledge deficits as an adaptation constraint (*very high confidence*). Often this demand for more information is linked to concerns regarding decision making under uncertainty about the future (*medium evidence*, *medium agreement*; Tribbia and Moser, 2008; Moser, 2010a; Whitmarsh, 2011; Stoutenborough and Vedlitz, 2013). A broad range of guidance on adaptation planning and implementation continues to emerge as a means of empowering actors to pursue adaptation efforts (Clar et al., 2013; EC, 2013; FAO, 2013; USCTI, 2013; Webb and Beh, 2013), and the World Meteorological Organization has emphasized the importance of climate services for vulnerability and disaster risk reduction (WMO, 2011).

A number of recent studies have investigated the extent to which education and knowledge about climate change influences perceptions of risk (Hamilton, 2011; McCright and Dunlap, 2011; Milfont, 2012). For example, studies suggest overconfidence in the ability of actors to manage risk (Wolf et al., 2010; Kuruppu and Liverman, 2011) or differences in the perception of climate risk between actors and governing institutions (Patt and Schröter, 2008a) can constrain adaptation (*medium evidence*, *medium agreement*). Therefore, capacity building through education, training, and information access represents a valuable opportunity for adaptation (Section 16.3.1.1).

Nevertheless, numerous recent studies caution that addressing knowledge deficits may not necessarily lead to adaptive responses (*very high confidence*; Kellstedt et al., 2008; Tribbia and Moser, 2008; Adger et al., 2009; Malka and Krosnick, 2009; Moser, 2010b; Preston et al., 2011b; Kahan et al., 2012; Lemos et al., 2012). Research from the USA indicates that those most informed about science and climate change are not necessarily the most concerned about its potential consequences (Kellstedt et al., 2008; Kahan et al., 2012), although these findings run counter to research from New Zealand, where increased knowledge translated into increased public concern and efficacy (Milfont, 2012). Recent research also indicates that multiple factors influence how knowledge is perceived including political affiliation (Hamilton, 2011; McCright and Dunlap, 2011), educational attainment (McCright and Dunlap, 2011), and the confidence placed on different information sources (Sundblad et al., 2009). Various studies have questioned a common assumption in the climate change literature that improvements in climate information are needed to facilitate adaptation

Box 16-3 | Rates of Change as a Cross-Cutting Constraint

Future rates of global change will have a significant influence on the demand for, and costs of, adaptation (*very high confidence*). Since the AR4, new research has confirmed the commitment of the Earth system to future warming (Lowe et al., 2009; Armour and Roe, 2011; WGI AR5 Section 12.5) and elucidated a broad range of tipping points or "key vulnerabilities" that would result in significant adverse consequences should they be exceeded (Lenton et al., 2008; Rockstrom et al., 2009; see also Chapter 19). While the specific rate of climate change to which different ecological communities or individual species can adapt remains uncertain (Sections 16.3.2.3, 16.4.1), more rapid rates of change can constrain adaptation of natural systems (Hoegh-Guldberg, 2008; Gilman et al., 2008; Maynard et al., 2008; CCSP, 2009; Hallegatte, 2009; Malhi et al., 2009a,b; Thackeray et al., 2010; Lemieux et al., 2011; Fankhauser and Soare, 2013; see also Sections 4.3.2.5, 5.5.6), particularly in the presence of other environmental pressures (*very high confidence*; Brook et al., 2008). Literature suggests that the near-term economic costs of societal adaptation may be substantial, and those costs increase incrementally over time as the climate changes (Section 17.4.4). Therefore, higher rates or magnitudes of climate change may reduce the effectiveness of some adaptation options, and higher costs for adaptation may be incurred (New et al., 2011; Stafford Smith et al., 2011; Peters et al., 2013; see also Section 16.6). However, more rapid rates of change may also create greater incentives for adaptation, resulting in a faster pace of implementation (Travis and Huisenga, 2013).

Although rapid socioeconomic change, including economic development and technological innovation and diffusion, can enhance adaptive capacity (Section 16.3.1), it can also pose constraints (*very high confidence*; Section 20.3.2). Globally, economic losses from climate extremes are doubling approximately every 1 to 2 decades owing to increasing economic exposure (Pielke Jr. et al., 2008; Baldassarre et al., 2010; Bouwer, 2011; Gall et al., 2011; Munich Re, 2011; IPCC, 2012; Preston, 2013). Such losses are associated with high interannual variability (Preston, 2013), but current trends are projected to continue in future decades (Pielke Jr., 2007; Montgomery, 2008; O'Neill et al., 2010; UN DESA Population Division, 2011; Preston, 2013; see also Section 10.7.3), although losses may decline relative to growth in gross domestic product (GDP; IPCC, 2012). In addition, population growth and economic development can lead to greater resource consumption and ecological degradation (Alberti, 2010; Chen et al., 2010; Raudsepp-Hearne et al., 2010; Liu et al., 2012), which can constrain adaptation in regions where livelihoods are closely linked to ecosystem goods and services (*very high confidence*; Badjeck et al., 2010; Marshall, 2010; Warner et al., 2010; see also Section 16.3.2.3 and Box CC-EA). The adaptation literature also suggests that successful adaptation will be dependent in part on the rate at which institutions can learn to adjust to the challenges and risks posed by climate change and implement effective responses (*very high confidence*; Adger et al., 2009; Moser and Ekstrom, 2010; Stafford Smith et al., 2011).

(Dessai et al., 2009; Hulme et al., 2009; Wilby and Dessai, 2010; Verdon-Kidd et al., 2012; see also Section 2.4). Similarly, multiple authors have questioned the utility and robustness of vulnerability metrics and indices for informing adaptation decision making (Barnett et al., 2009; Klein, 2009; Hinkel, 2011; Preston et al., 2011b).

Similar tensions arise with respect to the role of traditional knowledge in adaptation. For example, cultural preferences regarding the value of traditional versus more formal scientific forms of knowledge influence what types of knowledge, and therefore adaptation options, are considered legitimate (Jones and Boyd, 2011). In the Arctic, Inuit traditional knowledge (*Inuit Qaujimajatuqangit*, IQ) encompasses all aspects of traditional Inuit culture including values, world-view, language, life skills, perceptions, and expectations (Nunavut Social Development Council, 1999; Wenzel, 2004). IQ includes, for example, weather forecasting, sea ice safety, navigation, and hunting and animal preparation skills that may have value for managing climate risk. Yet, as noted in the AR4 and more recent studies, these skills are declining among youth (*medium evidence*, *medium agreement*; Adger et al., 2007; Pearce et al., 2011). Increasing reliance on non-traditional forecasting (national weather office forecasts) and other technologies (GPS) in Arctic communities is in part responsible for increased risk taking when traveling on the land and sea ice (*medium evidence*, *medium agreement*; Aporta and Higgs, 2005; Ford et al., 2006; Pearce et al., 2011). Collectively, the recent literature suggests the extent to which knowledge acts to constrain or enable adaptation is dependent on how that knowledge is generated, shared, and used to achieve desired adaptation objectives (*very high confidence*; Patt et al., 2007; Nelson et al., 2008; Tribbia and Moser, 2008; Moser, 2010a,b).

Individual, institutional, and societal knowledge influences the capacity to develop and use technologies to achieve adaptation objectives (*very high confidence*; UNFCCC, 2006; Adger et al., 2007). The AR4 noted the role of technology in contributing to spatial and temporal heterogeneity in adaptive capacity and the potential for technology to constrain

adaptation or create opportunities (Adger et al., 2007). Key considerations with respect to technology as an adaptation constraint include (1) availability; (2) access (including the capacity to finance, operate, and maintain); (3) acceptability to users and affected stakeholders; and (4) effectiveness in managing climate risk (Adger et al., 2007; Dryden-Cripton et al., 2007; van Aalst et al., 2008; see also Sections 9.4.4, 11.7, 14.2.4, 15.4.3). Although technology has implications for regional adaptive capacity (e.g., Sections 22.4.5.7, 27.3.6.2, 29.6.2), in-depth exploration of technology in the adaptation literature is often associated with specific sectors (Howden et al., 2007; Bates et al., 2008; van Koningsveld et al., 2008; EPA, 2009; Parry et al., 2009; Zhu et al., 2010). For example, Howden et al. (2007) note the importance of technology options for facilitating adaptation including applications of existing management strategies as well as introduction of innovative solutions such as bio- and nanotechnology (see also Hillie and Hlophe, 2007; Bates et al., 2008; Fleischer et al., 2011). Several studies from Africa have explored how different factors drive awareness, uptake, and use of adaptation technologies for agriculture (Nhemachena and Hassan, 2007; Hassan and Nhemachena, 2008; Deressa et al., 2009, 2011). While such literature identifies specific adaptation technology options, and in some cases the costs associated with their implementation, quantitative understanding of the extent to which improving technology will enhance adaptive capacity or reduce climate change impacts remains limited (Piao et al., 2010).

16.3.2.2. Physical Constraints

The capacity of human and natural systems to adapt to a changing climate is linked to characteristics of the physical environment including the climate itself. Recent studies have suggested that the effort required to adapt to an increase in global mean temperature of 4°C by 2100 may be significantly greater than adapting to lower magnitudes of change (*very high confidence*; Fung et al., 2011; Gemenne, 2011; New et al., 2011; Nicholls et al., 2011; Stafford Smith et al., 2011; Thornton et al., 2011; Zelazowski et al., 2011; see also Section 19.5.1). This challenge arises from the magnitude of climate change, as well as the rate (Box 16-3).

A variety of non-climatic physical factors also can constrain adaptation efforts of natural systems (*very high confidence*). For example, migration can be constrained by geographical features such as lack of sufficient altitude to migrate vertically or barriers posed by coastlines or rivers (Clark et al., 2011). Alternatively, Lafleur et al. (2010) identify soil conditions as a factor that may influence the migration of North American forests in response to climate change. Such physical barriers to migration can also arise from human activities. Feeley and Silman (2010) note that anthropogenic land use change can constrain the migration of Andean plant species to higher altitudes. Meanwhile, Titus et al. (2009) analyze state and local land use plans along the U.S. Atlantic coast and conclude that approximately 60% of coastal land below 1 meter in elevation is anticipated to be developed in the future, posing a physical barrier to inland migration of wetlands (see also Bulleri and Chapman, 2010; Jackson and McIlvenny, 2011). Collectively, such physical constraints can reduce available migration corridors and the distances over which migration is a feasible adaptive response.

Physical constraints have important implications for human adaptation as well (*medium evidence*, *high agreement*). For example, the distribution and abundance of water is a feature of the physical environment that is influenced by climate. Human consumption of freshwater increasingly is approaching the sustainable yield of surface and groundwater systems in a number of global regions (Shah, 2009; Pfister et al., 2009, 2011a,b; see also Sections 3.3.2, 3.5). Water-dependent enterprises in such regions may therefore have reduced flexibility to cope with transient or long-term reductions in water supply. This in turn influences the portfolio of adaptation actions that can be implemented effectively to manage risk to water security and, subsequently, agriculture and food security (Hanjra and Qureshi, 2010) as well as energy security (Voinov and Cardwell, 2009; Dale et al., 2011). Similarly, water quality and soil quality can constrain agricultural activities and therefore the capacity of agricultural systems to adapt to a changing climate (Delgado et al., 2011; Kato et al., 2011; Lobell et al., 2011; Olesen et al., 2011).

It is important to note, however, that these physical characteristics of the environment are often amenable to management (*very high confidence*). The AR4 presented case studies where adaptive capacity was linked to the ability of human populations or communities to access physical capital (Adger et al., 2007), such as machinery or infrastructure, to manage the environment and associated risks. Similar findings have appeared in more recent studies (Paavola, 2008; Thornton et al., 2008; Iwasaki et al., 2009; Badjeck et al., 2010; Nelson et al., 2010a,b). Human modification of the physical environment is particularly apparent in urban areas, where the location and design of buildings and infrastructure influence vulnerability to climate variability and change (Section 8.2.2.2). However, past decisions regarding the built environment and its need for continual maintenance can constrain future adaptation options and/or their costs of implementation (Section 16.3.2.10).

16.3.2.3. Biological Constraints

Since the AR4, the literature on biological (including behavioral, physiological, and genetic) tolerances of individuals, populations, and communities to climate change and extremes has continued to expand (Sections 4.4, 5.5.6, 6.2). This has resulted in a significant increase in the number of studies describing mechanisms by which biological factors can constrain the adaptation options for humans, nonhuman species, and ecological systems more broadly. In particular, biological characteristics influence the capacity of organisms to cope with increasing climate stress *in situ* through acclimation, adaptation, or behavior (Jensen et al., 2008; Somero, 2010; Tomanek, 2010; Aitken et al., 2011; Donelson et al., 2011; Gale et al., 2011; Sorte et al., 2011) as well as the rate at which organisms can migrate to occupy suitable bioclimatic regions (*very high confidence*; Morin and Thuiller, 2009; Hill et al., 2011; Feeley et al., 2012). Studies of humans also find age and geographic variation among populations with respect to perceptions of thermal comfort in indoor and outdoor space, which in turn influences the use of technologies (e.g., air conditioning, vegetation) and behavior to adjust to the thermal environment (Indraganti, 2010; Chen and Chang, 2012; Yang et al., 2012; Fuller and Bulkeley, 2013; Müller et al., 2013).

The biological capacity for migration among nonhuman species is linked to characteristics such as fecundity, phenotypic and genotypic variation, dispersal rates, and interspecific interactions (Aitken et al., 2008; Engler et al., 2009; Hellmann et al., 2012). For example, Aitken et al. (2008)

argue that migration rates of tree species necessary to track a changing climate are higher than what has been observed since the last glaciation. However, Kremer et al. (2012) note that long-distance gene flow of tree species can span distances in one generation that are greater than habitat shifts predicted under climate change. Additional research is needed to clarify the capacity of species and communities to migrate in response to a changing climate.

The degradation of environmental quality is another source of constraints (*very high confidence*; Côté and Darling, 2010), with multiple studies including natural capital as a foundation for sustainable livelihoods (Paavola, 2008; Thornton et al., 2008; Iwasaki et al., 2009; Badjeck et al., 2010; Nelson et al., 2010a,b). Non-climatic stresses to ecological systems can reduce their resilience to climate change as evidenced by studies on coral reefs and marine ecosystems, tropical forests, and coastal wetlands (*very high confidence*; Diaz and Rosenberg, 2008; Kapos and Miles, 2008; Malhi et al., 2009a,b; Afreen et al., 2011; see also Section 4.2.4 and Box CC-CR). For example, several studies have noted interactions between anthropogenic land use change and species migration rates on the risk of extirpation (Feeley et al., 2010; Yates et al., 2010; Cabral et al., 2013; Svenning and Sandel, 2013).

Ecological degradation also reduces the availability of ecosystem goods and services for human populations (*very high confidence*; Nkem et al., 2010; Tobey et al., 2010; see also Sections 4.4.3, 6.4.1). For example, degradation of coastal wetlands and coral reef systems may reduce their capacity to buffer coastal systems from the effects of tropical cyclones (Das and Vincent, 2009; Tobey et al., 2010; Gedan et al., 2011; Keryn et al., 2011; Box CC-EA). Similarly, soil degradation and desertification can reduce crop yields and the resilience of agricultural and pastoral livelihoods to climate stress (Iglesias et al., 2011; Lal, 2011).

Ecosystem constraints can also arise from non-native species, including pests and disease, that compete with endemic species (Hellman et al., 2008; Dukes et al., 2009; Moser et al., 2011; Ziska et al., 2011; Pautasso et al., 2012; Svobodová et al., 2013; see also Section 4.2.4.6). Climate change could reduce the effectiveness of current control mechanisms for invasive species (*very low confidence*; Hellmann et al., 2008). However, studies also indicate that uncertainty associated with predictions of future pests, disease, and invasive species remains high (Dukes et al., 2009).

16.3.2.4. Economic Constraints

The AR4 concluded that adaptive capacity is influenced by the entitlements of actors to economic resources and by larger macro-level driving forces such as economic development and trends in globalization (Adger et al., 2007). More recent literature continues to identify economic constraints associated with adaptation. However, such constraints often involve the financing of discrete adaptation options (e.g., Matasci et al., 2013; Islam et al., 2014). This chapter draws a distinction between such financial constraints (Section 16.3.2.5) and economic constraints, which are associated with broader macroeconomic considerations.

Long-term trends in economic development as well as short-term dynamics in economic systems can have a significant influence on the capacity of actors to adapt to climate change (*very high confidence*; Section 16.3.1.1). Multiple authors, for example, discuss the concept of "double exposure" where actors are subjected to stresses associated with climate change as well as those associated with economic disruptions such as the recent global financial crisis or other stresses (Leichenko et al., 2010; Silva et al., 2010; Leichenko, 2012; Jeffers, 2013; McKune and Silva, 2013). Similarly, Kiem and Austin (2013) argue that prevailing economic conditions have an important influence on the capacity of Australian farmers to cope with drought.

The implications of economic constraints vary among different sectors that have differential vulnerability to climate change. Economies that are disproportionately composed of climate-sensitive sectors such as agriculture, forestry, and fisheries may be particularly vulnerable to the effects of climate change and may encounter greater constraints on their capacity to adapt (*very high confidence*). Such economies occur disproportionately in the developing world (Thornton et al., 2008; Allison et al., 2009; Feng et al., 2010; Füssel, 2010), although multiple studies have explored climate-sensitive regional economies in developed nations as well (Edwards et al., 2009; Leichenko et al., 2010; Aaheim et al., 2012; Kiem and Austin, 2013). Poverty and development deficits that are linked to economic conditions also exist in urban areas (Sections 8.1.3, 8.3.2.1).

While economic development and diversification are generally seen as factors that can ameliorate resource deficits (Sections 20.2.1.2, 20.3.2), certain economic enterprises can constrain adaptation. For example, the AR4 noted that activities such as shrimp farming and conversion of coastal mangroves, though profitable in an economic sense, can exacerbate vulnerability to sea level rise (Agrawala et al., 2005; Adger et al., 2007). More recent studies have demonstrated that economic development and urbanization of hazardous landscapes may increase human exposure to extreme weather events and climate change, resulting in greater economic losses and risks to public health and safety (Baldassare et al., 2010; IPCC, 2012; Preston, 2013). Economic development also can put pressure on natural resources and ecosystems that can constrain their capacity to adapt (Titus et al., 2009; Sydneysmith et al., 2010; see also Sections 16.3.2.3, 20.3.2). The extent to which economic development creates opportunities or constrains adaptation is dependent on the development pathway (Section 20.6). Low resource-intensive economic growth can enhance adaptive capacity while minimizing externalities of development that can increase vulnerability of human and natural systems (Section 20.6).

16.3.2.5. Financial Constraints

In addition to broader macroeconomic constraints on adaptation (Section 16.3.2.4), the implementation of specific adaptation strategies and options can be constrained by access to financial capital (*very high confidence*). Financial capital can manifest in a variety of forms including credit, insurance, and tax revenues, as well as earnings of individual households or private entities. The AR4 concluded that the global costs of adaptation could be quite substantial over the next several decades (Adger et al., 2007). More recent studies suggest costs on the order of US$75 to US$100 billion per year by 2050 (Section 17.4; Table 17-2). In the context of the UNFCCC, mechanisms have been established to help meet these costs. The Least Developed Country Fund was established to assist

developing nations in generating National Adaptation Plans of Action (Sections 14.4.4, 15.2.3). The Adaptation Fund was established within the context of the UNFCCC to finance adaptation in developing nations through the sale of certified emissions reductions (CERs) credits under the Clean Development Mechanism (Sections 14.3.2, 15.2.2.1). Nevertheless, declines in CER credit prices since early 2011 have reduced the flow of revenue to the Adaptation Fund (Adaptation Fund Board, 2013), and the demand for adaptation finance in general is larger than the current availability of resources represented through these funds (Bouwer and Aerts, 2006; Flåm and Skjærseth, 2009; Hof et al., 2009). Furthermore, developing a framework for the equitable and effective allocation of adaptation funds to developing nations is a non-trivial challenge (Smith et al., 2009a; Barr et al., 2010).

Overseas development assistance (ODA) represents another mechanism for channeling financial capital into adaptation programs and projects. However, multiple authors have identified potential constraints associated with the use of ODA for financing adaptation, including concerns among donors for the effectiveness of ODA (Kalirajan et al., 2011), lack of incentives among donors to allocate ODA to adaptation (Buob and Stephan, 2013), and potential for allocation of ODA to adaptation to reduce the availability of funds for achieving development goals (Ayers and Huq, 2009).

The potential for finance to constrain adaptation also emerges from a broad range of recent case studies exploring adaptive capacity in different sector and regional contexts, although finance is often identified as just one of a broad range of resource constraints (Paavola, 2008; Jantarasami et al., 2010; Moser and Ekstrom, 2010; Osbahr et al., 2010; Biesbroek et al., 2013a). Investigations of farming communities in Africa have identified finance as a key determinant of vulnerability and adaptive capacity of farmers to climate variability and change (Nhemachena and Hassan, 2007; Hassan and Nhemachena, 2008; Deressa et al., 2009, 2011). Islam et al. (2014) cite access to credit as a key constraint on adaptation among fishing communities in Bangladesh, and financial constraints have also been documented in municipal governments in South Africa (Pasquini et al., 2013). Huntington et al. (2012) question whether relocating the 184 Alaskan Native villages threatened by coastal erosion and inundation is politically feasible given the high costs, estimated at up to US$1 million per person or US$100 million per village on average.

Institutions in developed nations face constraints in funding adaptation options despite their comparatively high adaptive capacity. For example, Jantarasami et al. (2010) report that staff from U.S. federal land management agencies identified resource constraints as a key barrier to adaptation. Similarly, surveys and interviews with state and local government representatives in Australia indicate that the costs of investigating and responding to climate change are perceived to be significant constraints on adaptation at these levels of governance (Smith et al., 2008b; Gardner et al., 2010; Measham et al., 2011). However, Burch (2010) argues that financial constraints on adaptation reported by local governments in Canada are secondary to other institutional practices and cultures (Section 16.3.2.8).

Insurance represents a cross-cutting financial instrument that is relevant to a range of public and private institutions in both developing and developed nations. While insurance can represent an opportunity to influence decision making regarding climate risk management (Næss et al., 2005; Herweijer et al., 2009; see also Section 10.7), reduced accessibility and/or increased costs of insurance can constrain the utility of insurance as an adaptation option (Herwijer et al., 2009; Islam et al., 2014; see also Section 10.7).

16.3.2.6. Human Resource Constraints

The effectiveness of societal efforts to adapt to climate change is dependent on humans who are the primary agents of change (*very high confidence*). Human resources provide the foundation for intelligence gathering, the uptake and use of technology, as well as leadership regarding the prioritization of adaptation policies and measures and their implementation. Although the AR4 and subsequent adaptation literature identify human resources as one of the factors influencing adaptive capacity (Adger et al., 2007), there has been little attention given specifically to human resources as a constraint on adaptation by adaptation researchers. Rather the literature mentions human resources in two principal contexts. First, it highlights the linkages between the development of human resources and adaptive capacity more broadly. For example, Ebi and Semenza (2008) treat human resources as part of the portfolio of resources that can be harnessed to facilitate adaptation in the public health arena. Similarly, Nelson et al. (2010a,b) use human capital as one indicator of the capacity of rural communities to cope with climate impacts. In addition, a number of recent studies call attention to the role of leadership in enabling or constraining organizational adaptation (Gupta et al., 2010; Tompkins et al., 2010; van der Berg et al., 2010; Termeer et al., 2012). Murphy et al. (2009) discuss the emergence of institutions to build human resources in the climate change arena, including expanded higher education opportunities to build climate expertise as well as professional societies. Second, the literature highlights the finite nature of human resources as a need to prioritize adaptation efforts including the extent of engagement in participatory processes (van Aalst et al., 2008) as well as the selection of adaptation actions for implementation (Millar et al., 2007).

16.3.2.7. Social and Cultural Constraints

Adaptation can be constrained by social and cultural factors that are linked to societal values, world views, and cultural norms and behaviors (*very high confidence*; O'Brien, 2009; Moser and Ekstrom, 2010; O'Brien and Wolf, 2010; Hartzell-Nichols, 2011). These social and cultural factors can influence perceptions of risk, what adaptation options are considered useful and by whom, as well as the distribution of vulnerability and adaptive capacity among different elements of society (Grothmann and Patt, 2005; Weber, 2006; Patt and Schröter, 2008; Adger et al., 2009; Kuruppu, 2009; O'Brien, 2009; Nielsen and Reenberg, 2010; Wolf and Moser, 2011; Wolf et al., 2013). Although the AR4 noted that social and cultural constraints on adaptation have not been well researched, more recent literature has significantly expanded their understanding. As a case in point, the erosion of traditional knowledge among the Arctic Inuit is the consequence of a long-term process of changing livelihoods, technology, and sources of knowledge (Pearce et al., 2011; see also Section 16.3.2.1). Studies from the USA indicate that increasing demand

for amenity lifestyles is resulting in the settlement of individuals in locations where there is little experience or oral history regarding natural hazards—a phenomenon that subsequently influences risk perception and engagement in risk management (Heyd and Brooks, 2009; Gordon et al., 2013).

Different actors within and among societies experience different constraints, which result in differential adaptive capacities and preferences for adaptation options (Wolf et al., 2013). As discussed in the AR4, for example, gender can be a factor that constrains adaptation. Recent studies from Nepal and India report that adaptation decisions among women, in particular, can be constrained by cultural and institutional pressures that favor male land ownership (Jones and Boyd, 2011) and constrain access to hazard information (Ahmed and Fajber, 2009), respectively. Studies of evacuation during Hurricane Katrina suggest that females were more likely to evacuate New Orleans than males (Brunsma et al., 2010), as were individuals without sufficient resources and access to transportation (Cutter and Emrich, 2006). Studies from both the USA and UK find that the elderly do not necessarily perceive themselves as vulnerable to extreme heat events (Sheridan, 2007; Wolf et al., 2009), which may create disincentives to react to such events (Chapter 11).

Barriers to taking action have also been attributed to sense of place, which shapes individual identity (Adger et al., 2011, 2012; Fresque-Baxter and Armitage, 2012). Foresight (2011) notes that processes that constrain migration could be maladaptive, resulting in the abandonment of livelihoods or geographic locations. For example, Park et al. (2012) find that sense of place attachment among some wine grape growers in Australia precludes consideration for migration to other growing areas in response to a changing climate.

Case studies from multiple developing countries report that some actors view natural phenomena as being controlled by God, supernatural forces, or ancestral spirits that are not amenable to human management (Sehring, 2007; Schipper, 2008; Byg and Salick, 2009; Mustelin et al., 2010; Kuruppu and Liverman, 2011; Artur and Hilhorst, 2012). Such perspectives are not confined to the developing world. Surveys conducted after Hurricane Katrina also indicated that religious beliefs were a factor influencing the decision to remain rather than evacuate (Brunsma et al., 2010). Yet, religion was also identified as a factor that enabled affected individuals to cope with the stress of the event.

16.3.2.8. Governance and Institutional Constraints

Research conducted since the AR4 has expanded understanding of adaptation constraints associated with governance, institutional arrangements, and legal and regulatory issues. Adaptation to climate change will necessitate the mobilization of resources, decision making, and the implementation of specific policies by societal institutions (Huang et al., 2011). Yet, these processes may be most effective when they are aligned to the given context and group of actors (Berkhout, 2012; Garschagen, 2013). The adaptation literature provides extensive evidence that institutional capacity is a key factor that can potentially constrain the adaptation process (*very high confidence*; Berkhout, 2012). Lesnikowski et al. (2013), for example, find that planned adaptation by the public health sector among different nations is significantly associated with national GDP. Similarly, it has been argued that U.S. institutions across different levels of governance lack the mandate, information, and/or professional capacity to select and implement adaptation options (National Research Council, 2009). Institutional capacity may be linked to the level of priority assigned to adaptation (Keskitalo et al., 2010; Westerhoff et al., 2010; Maibach et al., 2011; Measham et al., 2011; Sowers et al., 2011). For example, Ebi et al. (2009) argue that U.S. public health agencies allocate less than US$3 million per year to address climate change, yet a budget greater than US$200 million is needed to adequately address the problem. Keskitalo (2010) and Lesnikowski et al. (2013) find that adaptation efforts are associated with the extent to which institutions prioritize environmental management more broadly. Corruption within institutions may also undermine adaptation efforts, as evidenced by empirical studies among multiple nations (Lesnikowski et al., 2013), as well as case studies within nations (Schilling et al., 2012).

A key role that institutions play in facilitating adaptation is through legal and regulatory responsibilities and authorities (*very high confidence*). Multiple studies have documented the adaptation constraints affecting institutions in Australia engaged in the development of local and regional planning policy (Pini et al., 2007; Measham et al., 2011; Matthews, 2013). Similar capacity constraints have been observed within institutions governing Canada's Inuit population (Ford et al., 2010). Li and Huntsinger (2011) observe how increasing land privatization and the institutionalization of rigid land tenure in the Inner Mongolia region of China have reduced the resilience of pastoralists to cope with drought, although the lack of secure land tenure has been found to constrain adaptation in other contexts (Almansi, 2009; Ebi et al., 2011; Hisali et al., 2011; Larson, 2011; see also Sections 8.4.2.2, 9.3.5.1.3). In addition to such capacity issues, multiple studies from both developed and developing nations suggest that the current structure of institutions and regulatory policies may be poorly aligned to achieve adaptation objectives (Craig, 2010; Spies, 2010; Stillwell et al., 2010; Stuart-Hill and Schulze, 2011; Eisenack and Stecker; 2012; Huntjens et al., 2012; Herrfahrdt-Pähle, 2013). Changing legal principles to accommodate more forward-looking adaptation responses as opposed to basing them on historical precedent and practice may be a difficult process (Craig, 2010; McDonald, 2011).

Adaptation can also be constrained owing to the complexities of governance networks that are often composed of multiple actors and institutions such as government agencies, market actors, NGOs, as well as informal community organizations and social networks (*very high confidence*; Rosenau, 2005; Adger et al., 2009; Juhola and Westerhoff, 2011; Carlsson-Kanyama et al., 2013; Sosa-Rodriguez, 2013). Coordination among these different actors is important for facilitating adaptation decision making and implementation (Young, 2006; van Nieuwaal et al., 2009; Grothmann, 2011). Yet, different actors may have different objectives, jurisdictional authority, as well as levels of power or resources. Adaptation efforts may recognize these constraints, but do not necessarily articulate institutional arrangements that facilitate their coordination and reconciliation to achieve common adaptation objectives (Zinn, 2007; Preston, 2009; Birkmann et al., 2010; see also Section 15.5.1). This may arise, in part, from the dominant focus of the adaptation discourse on formal, public institutions of governance

(Eisenack et al., 2012), although work examining the role of private institutions has emerged recently (Tompkins et al., 2010; CDP, 2012; Mees et al., 2012; Taylor et al., 2012; Tompkins and Eakin, 2012; EBI, 2013; see also Section 14.2.4).

Actors and institutions associated with different scales may have different perceptions of the need for adaptation as well as the factors that constrain or enable adaptation (*very high confidence*; Biesbroek et al., 2011). In this context, scale refers to analytical dimensions used to study adaptation (including spatial, temporal, institutional, or jurisdictional), and each scale can be comprised of multiple levels (e.g., local to global in the context of spatial scales or household to central government in the context of jurisdictions of governance) (Cash et al., 2006; Adger et al., 2009). A large number of studies have emerged since the AR4 that focus on how local adaptation efforts are constrained by higher levels of governance, such as state or federal governments or private companies (Urwin and Jordan, 2008; Huntjens et al., 2010; Abel et al., 2011; Measham et al., 2011; Pittock, 2011; Westerhoff et al., 2011; Amaru and Chhetri, 2013; Carlsson-Kanyama et al., 2013; Mukheibir et al., 2013; Sosa-Rodriguez, 2013). This has led some to question whether it is appropriate to consider adaptation as an exclusively local process (Burton et al., 2008; Preston et al., 2013b). For example, a study of adaptation policy initiatives in EU member countries concluded that central governments can play a significant role in supporting local adaptation policies. However, in cases where there is weak top-down leadership on adaptation, it may be useful to have less centralized mechanisms for supporting local adaptation efforts (Keskitalo, 2010). In addition, EU funding has enabled local adaptation even in the absence of funding from the relevant EU member state (Keskitalo, 2010), suggesting opportunities exist for transnational governance to overcome adaptation constraints.

Other authors have also noted that informal social institutions may help to extend the reach of formal government actors (Wolf et al., 2010; Juhola and Westerhoff, 2011) or drive adaptation processes when formal actors are unable to do so (Measham and Preston, 2012). Adaptation planning and implementation thus creates new governance challenges, and new institutions and bridging organizations may be needed to facilitate integration of complex planning processes across scales (*medium evidence*, *high agreement*; Preston, 2009; National Research Council, 2010; UKCIP, 2011).

16.3.2.9. Constraints and Competing Values

A number of the aforementioned types of adaptation constraints arise from a common cause—the differential values of societal actors and the trade-offs associated with prioritizing and implementing adaptation options (*very high confidence*; Haddad, 2005; UNEP, 2011; see also Section 2.3.3 and Table 16-2). At the international level, for example, agreements such as the Bali Action Plan (UNFCCC, 2007a) and Cancun Adaptation Framework (UNFCCC, 2011) indicate that deliberation over how the adaptation needs of least developed countries will be financed has become central to the UNFCCC policy agenda (see also UNFCCC, 2007b; Ayers and Huq, 2009; Dellink et al., 2009; Flåm and Skjærseth, 2009; Denton, 2010; Patt et al., 2010a). Yet the extent to which the developed world bears responsibility for compensating the developing world for climate impacts has been a contentious issue (Hartzell-Nichols, 2011). Rayner and Jordan (2010) and Brouwer et al. (2013) report concern among EU water policy makers that adaptation may undermine efforts to maintain water quality. For example, technological solutions to enhance water supply in a changing climate may occur at the expense of water quality. Alternatively, placing adaptation on the policy agenda may create the perception that climate change will eventually necessitate the acceptance of reduced water quality. At the local level, Measham et al. (2011) report that some local governments in Australia find it difficult to pursue adaptation efforts owing to perceived conflicts between potential adaptation options and the values and preferences of individuals and stakeholder groups within the community.

Such potential differences among stakeholders regarding adaptation options may result in some actions being simultaneously perceived as adaptive and maladaptive (*limited evidence*, *medium agreement*; Bardsley and Hugo, 2010). Maladaptation arises from the implementation of adaptation options that increase the vulnerability of individuals, institutions, sectors, or regions (Barnett and O'Neill, 2010). Individuals or institutions may have specific management objectives or values that they seek to achieve or maintain through adaptation (Section 16.2, Table 16-2). For every objective, however, there may be multiple adaptation options, each of which is associated with a particular set of costs, benefits, and externalities. For example, biotechnology may contribute to the development of drought- and pest-resistant cultivars that can maintain or enhance yields despite more challenging climate conditions. Yet, ecological and public health concerns over the use of biotechnology and genetically modified crops, in particular, can constrain the use of such technologies (Table 16-2). Agricultural producers may view biotechnology as an adaptive response, while some consumers may view it as a maladaptation that increases risks to ecosystems and food security. Similar types of trade-offs can be identified across different sectors (Table 16-2), and thus a challenge in adaptation planning and implementation is determining who decides what options are adaptive or maladaptive and successful or unsuccessful. The potential for maladaptation or for some adaptation options to undermine sustainability (Eriksen et al., 2011) suggests that actors may choose to regulate adaptation and deliberately constrain possible options to avoid adverse externalities (*very low confidence*).

Recognizing the potential for values conflicts to constrain adaptation, researchers and practitioners have advocated for so-called "no regrets" or "low regrets" adaptation strategies that create net benefits under the current climate as well as a range of future potential climates (Hallegatte, 2009; Heltberg et al., 2009). Such strategies can focus adaptation efforts on options where there are fewer perceived trade-offs (Preston et al., 2013b). However, identifying options that are perceived as having no regrets across all potential stakeholders may be quite difficult (Merz et al., 2010; Preston et al., 2013b), and it has been suggested such strategies may reduce the perceived need for more substantive adaptations necessary to protect highly vulnerable systems or avoid irreversible consequences (Preston et al., 2013b). Reconciling such trade-offs may necessitate deliberation among decision makers and other stakeholders regarding adaptation objectives and the manner in which competing or conflicting values can be reconciled to achieve outcomes (de Bruin et al., 2009b; McNamara and Gibson, 2009; McNamara et al., 2011; UNEP, 2011).

Table 16-2 | Examples of potential trade-offs associated with an illustrative set of adaptation options that could be implemented by actors to achieve specific management objectives.

Sector	Actor's adaptation objective	Adaptation option	Real or perceived trade-off	References
Agriculture	Enhance drought and pest resistance; enhance yields	Biotechnology and genetically modified crops	Perceived risk to public health and safety; ecological risks associated with introduction of new genetic variants to natural environments	Howden et al. (2007); Nisbet and Scheufele (2009); Fedoroff et al. (2010)
	Provide financial safety net for farmers to ensure continuation of farming enterprises	Subsidized drought assistance; crop insurance	Creates moral hazard and distributional inequalities if not appropriately administered	Productivity Commission (2009); Pray et al. (2011); Trærup (2011); O'Hara (2012); Vermeulen et al. (2012)
	Maintain or enhance crop yields; suppress opportunistic agricultural pests and invasive species	Increased use of chemical fertilizer and pesticides	Increased discharge of nutrients and chemical pollution to the environment; adverse impacts of pesticide use on non-target species; increased emissions of greenhouse gases; increased human exposure to pollutants	Gregory et al. (2005); Howden et al. (2007); Boxall et al. (2009)
Biodiversity	Enhance capacity for natural adaptation and migration to changing climatic conditions	Migration corridors; expansion of conservation areas	Unknown efficacy; concerns over property rights regarding land acquisition; governance challenges	Hodgson et al. (2009); West et al. (2009); Krosby et al. (2010); Levin and Petersen (2011)
	Enhance regulatory protections for species potentially at risk due to climate and non-climatic changes	Protection of critical habitat for vulnerable species	Addresses secondary rather than primary pressures on species; concerns over property rights; regulatory barriers to regional economic development	Clark et al. (2008); Ragen et al. (2008); Bernanzzani et al. (2012)
	Facilitate conservation of valued species by shifting populations to alternative areas as the climate changes	Assisted migration	Difficult to predict ultimate success of assisted migration; possible adverse impacts on indigenous flora and fauna from introduction of species into new ecological regions	Lovejoy (2005, 2006); McLachlan et al. (2007); Dunlop and Brown (2008)
Coasts	Provide near-term protection to financial assets from inundation and/or erosion	Sea walls	High direct and opportunity costs; equity concerns; ecological impacts to coastal wetlands	Nicholls (2007); Hayward (2008); Hallegatte (2009); Zhu et al. (2010)
	Allow natural coastal and ecological processes to proceed; reduce long-term risk to property and assets	Managed retreat	Undermines private property rights; significant governance challenges associated with implementation	Rupp-Armstrong and Nicholls (2007); Hayward (2008); Abel et al. (2011); Titus (2011)
	Preserve public health and safety; minimize property damage and risk of stranded assets	Migration out of low-lying areas	Loss of sense of place and cultural identify; erosion of kinship and familial ties; impacts to receiving communities	Hess et al. (2008); Heltberg et al. (2009); McNamara and Gibson (2009); Adger et al. (2011)
Water resources management	Increase water resource reliability and drought resilience	Desalination	Ecological risk of saline discharge; high energy demand and associated carbon emissions; creates disincentives for conservation	Adger and Barnett (2009); Barnett and O'Neill (2010); Becker et al. (2010, 2012); Rygaard et al. (2011); Tal et al. (2011)
	Maximize efficiency of water management and use; increase flexibility	Water trading	Undermines public good/social aspects of water	Alston and Mason (2008); Bourgeon et al. (2008); Donohew (2008); Mooney and Tan (2012); Tan et al. (2012)
	Enhance efficiency of available water resources	Water recycling/reuse	Perceived risk to public health and safety	Hartley (2006); Dolcinar et al. (2011)

16.3.2.10. Consideration of Cross-Scale Dynamics

The AR4 noted that adaptation processes can be constrained by interactions and dynamics within or among different scales (Adger et al., 2007). Recent literature since the AR4 has expanded understanding of vulnerability and adaptive capacity as a cross-scale and multilevel process. The vulnerabilities of different communities, regions, and sectors are linked through processes and feedbacks that span multiple scales and levels (*medium evidence*, *high agreement*). Adger et al. (2008) and Eakin et al. (2009) refer to this phenomenon as "nested and teleconnected vulnerability."

A number of recent studies focused on agriculture and global commodities provide evidence of this phenomenon. Adger et al. (2008) and Eakin et al. (2009) illustrate such teleconnected vulnerability with case studies of coffee production. Although coffee is a global commodity, the majority of production occurs in developing nations among small-scale farmers. As such, household vulnerability and adaptive capacity among coffee farmers is linked to global markets and coffee prices as well as local environmental conditions and policies. Such interactions were also apparent in 2006–2008 and again in 2010–2011 when global food commodity prices increased sharply in part due to the impacts of extreme weather events on food-producing regions (FAO, 2011). The resulting increase in food prices benefited producers that were unaffected by the drought and were able to capitalize on higher prices, but higher prices adversely affected consumer welfare and food security (Abbott and de Battisti, 2009; Woden and Zaman, 2009; FAO, 2011).

Similar constraints on adaptation arise in the context of transboundary water resources where river management is influenced by processes occurring at different jurisdictional levels (i.e., local, regional, national, and international water policies and management practice) as well as different spatial levels (e.g., linkages between global climate change and climate trends at more regional or local levels) (Iglesias et al., 2007;

Goulden et al., 2009; Huntjens et al., 2010; Krysanova et al., 2010; Timmerman et al., 2011; Wilby and Keenan, 2012; Milman et al., 2013).

Constraints on adaptation are also associated with temporal scaling. A key factor constraining future adaptation options and costs is path dependence (*very high confidence*), which Preston (2013, p. 719) defines as "the dependence of future societal decision processes and/or socio-ecological outcomes on those that have occurred in the past." Libecap (2010) suggests that water infrastructure developed in the U.S. West in the late-19th and early 20th centuries has constrained management choice regarding water allocation in the present. Chhetri et al. (2010) suggest similar constraints may exist for the U.S. agricultural industry in the future owing to constraints on farmers' capacity to alter management practices and technology in response to a changing climate. Major development of water management and allocation systems in watersheds of Australia and the U.S. Southeast over the latter half of the 20th century occurred during periods of favorable rainfall relative to long-term instrumental and paleo records (Jones and Pittock, 2002; Jones, 2010; Chiew et al., 2011; Pederson et al., 2012), and thus those systems were adapted to conditions that were not representative of the long-term risk of extensive drought (Jones and Pittock, 2002; Jones, 2010; Connell and Grafton, 2011; Pederson et al., 2012).

Adjusting large-scale, complex systems and institutional behavior established by past decision making can be costly. The Australian government, for example, has engaged in a water management reform process since the 1980s (Connell and Grafton, 2011), and in recent years has committed more than AU$12.9 billion for a number of initiatives to address historical resource over-allocation and support sustainable water management practices in the Murray-Darling Basin (Commonwealth of Australia, 2010).

To avoid adverse outcomes associated with path dependence, literature on flexible adaptation pathways emphasizes the implementation of reversible and flexible options that allow for ongoing adjustment (Stafford Smith et al., 2011; Haasnoot et al., 2013). In addition, the literature on "real options" suggests that, under certain circumstances, there may be value in such flexible adaptation strategies or in delaying investments in certain adaptation options until new information or management options are available (Hertzler, 2007; Dobes, 2008; Jeuland and Whittington, 2013).

16.4. Limits to Adaptation

The various constraints discussed previously (Section 16.3.2) can, if sufficiently severe, pose limits to the ability of actors to adapt to climate change (*medium evidence*, *high agreement*; Meze-Hausken, 2008; Adger et al., 2009; O'Brien, 2009; Moser and Ekstrom, 2010; Dow et al., 2013a,b). A limit is reached when adaptation efforts are unable to provide an acceptable level of security from risks to the existing objectives and values and prevent the loss of the key attributes, components, or services of ecosystems (Box 16-1). For example, one of the key messages from the WGII AR5 chapter on Africa (Chapter 22) is, "Progress is being achieved on managing risks to food production from current climate variability but these will likely not be sufficient to address long-term risks from climate change (*high confidence*)."

There are a variety of circumstances and terminology in the literature that imply adaptation limits including "thresholds" (Meze-Hausken, 2008; Briske et al., 2010; Washington-Allen et al., 2010); "regime shifts" (Washington-Allen et al., 2010); "tipping points" (Lenton et al., 2008; Kriegler et al., 2009); "dangerous climate change" (Mastrandrea and Schneider, 2004; Ford, 2009a); "reasons for concern" (Smith et al., 2009a); "planetary boundaries" (Rockström et al., 2009); or "key vulnerabilities" (Schneider et al., 2007; Hare et al., 2011; Johannessen and Miles, 2011; see also Section 19.6). In addition, terms such as barriers, constraints, and limits are sometimes used interchangeably. Owing to this diversity in language, this discussion builds on recent efforts to develop a common lexicon to facilitate research and practice (Hulme et al., 2007; Adger et al., 2009; Dow et al., 2013a,b; see also Section 16.2 and Box 16-1).

16.4.1. Hard and Soft Limits

Although limits to adaptation are at times described in the literature as fixed thresholds (Adger et al., 2009), recent studies have emphasized the need to consider the perspective of actors in defining adaptation limits (Adger et al., 2009; Dow et al., 2013 a,b; see also Sections 16.1-2) as well as the dynamic nature of both biophysical and socioeconomic processes that influence adaptation decision making and implementation (Park et al., 2012; Preston et al., 2013a; Islam et al., 2014). Informed by the distinctions drawn in the work of Meze-Hausken (2008), Adger et al. (2009), and Moser and Ekstrom (2010), one can distinguish between "hard" limits, those that will not change, and "soft" limits, which could change over time. For human actors, whether a limit is hard or soft is usefully evaluated at a given point in time by asking whether an adaptation response to manage an intolerable risk could emerge in the future. For example, projected climate change impacts in Europe indicate that increasing irrigation needs will be constrained by reduced runoff, demand from other sectors, and economic costs. As a consequence, by the 2050s, farmers will be limited by their inability to use irrigation to prevent damage from heat waves to crops (Sections 23.4.1, 23.4.3). For natural systems, whether a limit is hard or soft is defined by the rate and capacity of species and ecosystem responses relative to environmental changes (Shaw and Etterson, 2012).

Discussions of hard limits in the literature are often associated with thresholds in physical systems that, if exceeded, would lead to irreversible changes or the loss of critical structure or function (Lenton et al., 2008; Adger et al., 2009; IPCC, 2012). Such limits arise from the magnitude and/or rate of climate change (Box 16-3). For example, a number of physical thresholds in the Earth system have been proposed as posing potential limits to adaptation, particularly large-scale events such as irreversible melting of the Greenland or Antarctic ice sheets (Schneider and Lane, 2006a; Sheehan et al., 2008; Travis, 2010). Such physical thresholds, however, though relevant to understanding adaptation limits, are not necessarily limits in themselves as they neglect consideration for the adaptive capacity of natural and human systems (Adger et al., 2009; Leary et al., 2009; Dow et al., 2013a,b; Klein and Juhola, 2013; Preston et al., 2013a).

For species and ecosystems, hard limits to adaptation are often associated with exceedance of the physiological capacity of individual organisms

Box 16-4 | Historical Perspectives on Limits to Adaptation

Does human history provide insights into societal resilience and vulnerability under conditions of environmental change? Archeological and environmental reconstruction provides useful perspectives on the role of environmental change in cases of significant societal change, sometimes termed "collapse" (Diamond, 2005). These may help to illuminate how adaptation limits were either exceeded, or where collapse was avoided to a greater or lesser degree. Great care is necessary to avoid oversimplifying cause and effect, or overemphasizing the role of environmental change, in triggering significant societal change, and the societal response itself. Coincidence does not demonstrate causality, such as in the instance of matching climatic events with social crises through the use of simple statistical tests (Zhang et al., 2011), or through derivative compilations of historical data (deMenocal, 2001; Thompson et al., 2002; Drysdale et al., 2006; Butzer, 2012). Application of social theories may not explain specific cases of human behavior and community decision making, especially because of the singular importance of the roles of leaders, elites, and ideology (Hunt, 2007; McAnany and Yoffee, 2010; Butzer, 2012; Butzer and Endfield, 2012).

There are now roughly a dozen case studies of historical societies under stress, from different time ranges and several parts of the world, that are sufficiently detailed (based on field, archival, or other primary sources) for relevant analysis (Butzer and Endfield, 2012). These include Medieval Greenland and Iceland (Dugmore et al., 2012; Streeter et al., 2012), Ancient Egypt (Butzer, 2012), Colonial Cyprus (Harris, 2012), the prehistoric Levant (Rosen and Rivera-Collazo, 2012), Islamic Mesopotamia and Ethiopia (Butzer, 2012), the Classic Maya (Dunning et al., 2012; Luzzadder-Beach et al., 2012), and Colonial Mexico (Endfield, 2012). Seven such civilizations underwent drastic transformation in the wake of multiple inputs, triggers, and feedbacks, with unpredictable outcomes. These can be seen to have exceeded adaptation limits. Five other examples showed successful adaptation through the interplay of environmental, political, and socio-cultural resilience, which responded to multiple stressors (e.g., insecurity, environmental or economic crises, epidemics, famine). In these cases, climatic perturbations are identified as only one of many "triggers" of potential crisis, with preconditions necessary for such triggers to stimulate transformational change. These preconditions include human-induced environmental decline mainly through overexploitation.

Avoidance of limits to adaptation requires buffering feedbacks that encompass social and environmental resilience. Exceedance of limits occurred through cascading feedbacks that were characterized by social polarization and conflict that ultimately result in societal disruption. Political simplification undermined traditional structures of authority to favor militarism, while breakdown was accompanied or followed by demographic decline. Although climatic perturbations and environmental degradation did contribute to triggering many cases of breakdown, the most prominent driver at an early stage was institutional failure, which refers to the inability of societal institutions to address collective-action problems (Acheson, 2006). In these cases, collapse was neither abrupt nor inevitable, often playing out over centuries. Lessons from the implementation of adaptation responses over historical time periods in Mexico City suggest that some responses may create new and even more significant risks (Sosa-Rodriguez, 2010).

Recent work on resilience and adaptation synthesizes lessons from extreme event impacts and responses in Australia (Kiem et al., 2010). This further emphasizes an institutional basis for resilience, finding that government intervention through the provision of frameworks to enable adaptation is beneficial. Furthermore, it was found that a strong government role may be necessary to absorb a portion of the costs associated with natural disasters. On the other hand, community awareness and recognition of novel conditions were also found to be critical elements of effective responses. It would be useful to consider how lessons learned from historical experience may relate to the perceived multiple environmental changes characterized by the "Anthropocene" era (Crutzen, 2002).

or communities to adapt to changes in the climate (i.e., temperature, rainfall, and/or disturbance regimes; Peck et al., 2009), or to climate-induced changes in the abiotic environment (e.g., ocean circulation and stratification; Harley et al., 2006; Doney et al., 2012; see also Sections 16.3.2.2-3). Such systems tend to be those that persist at the upper limit of their climate tolerances (Sheehan et al., 2008; Benito et al., 2011; Dirnböck et al., 2011); those for which sustainability is closely tied to vulnerable physical systems (Johannessen and Miles, 2011); or those that are under significant pressure from non-climatic forces (Jenkins et al., 2011). For example, many species, including humans (Section 11.8.1)

and key food crops (e.g., wheat, maize, and rice; Sections 7.3.2, 11.8.2), are known to have thermal limits to survival. Similarly, increased ocean acidity is expected to reduce the ability of some marine organisms such as corals to grow, posing threats of significant ecosystem damage (Boxes CC-OA and CC-CR). Nevertheless, defining those limits remains challenging owing to system complexity and lack of information regarding responses across different levels of biological organization (Steffen et al., 2009; Wookey et al., 2009; Lavergne et al., 2010; Preston et al., 2013a). Furthermore, species have mechanisms for coping with climate change including phenotypic plasticity (Charmantier et al., 2008; Matesanz et al., 2010), genetic (evolutionary) responses (Bradshaw and Holzapfel, 2006; Gienapp et al., 2008; Visser, 2008; Wang et al., 2013), and range shifts (Colwell et al., 2008; Thomas, 2010; Chen et al., 2011; see also Section 16.3.2.3). Such mechanisms influence adaptation limits by extending the range of climate conditions with which individual organisms can cope *in situ* and/or enabling species to migrate over time to more suitable climates. Yet, more comprehensive assessments of such adaptive mechanisms are needed to develop robust understanding of ecological limits.

While human systems may also experience hard limits, such systems are influenced by exogenous climate change as well as endogenous processes such as societal choices and preferences (Adger et al., 2009). This creates the potential for limits encountered by actors to be soft. Although they may limit adaptation for the current planning horizon, they may be ameliorated in the future by changing circumstances. Various authors have noted that adaptation limits are socially constructed by human agency in that economics, technology, infrastructure, laws and regulations, or broader social and cultural considerations can limit adaptation (*medium evidence*; *high agreement*; Adger et al., 2009; de Bruin et al., 2009b; Flåm and Skjærseth, 2009; O'Brien, 2009; Wilbanks and Kates, 2010; McNamara et al., 2011; Morrison and Pickering, 2012; see also Section 16.3). Cost-benefit analyses and associated discount rates, for example, reflect a social value on investment returns (Section 17.4.1). Yet, Morgan (2011) notes that adaptation planning based on cost-benefit analysis can pose limits to adaptation by discounting the future economic benefits of adaptation actions and excluding non-market benefits. Meanwhile, increasing loss and damage from societal exposure and climate change may pose financial limits to the insurability of disaster risks (Section 10.7.3), which ultimately influences what activities can occur in certain locations. All of these factors are dynamic and can change over time. The Shared Socioeconomic Pathways, which have been designed to facilitate comparison of findings across modeling teams, reflect different perspectives on future changes in the capacity of actors to adapt (Kriegler et al., 2012; Ebi et al., 2013; Schweizer and O'Neill, 2013; van Ruijven et al., 2013). Given rising incomes and advances in knowledge and technology, a greater number of adaptation options may become available to a greater number of actors over time. In contrast, impediments to development, constraints on investments in adaptation, or rapid escalations in risk may increase the likelihood of experiencing a limit.

Societal assessments of risk and willingness to invest in risk management are subject to many influences (Renn, 2008; IPCC, 2012; see also Section 14.5), such as experience of a recent disaster, some of which can result in rapid changes (Ho et al., 2008; Breakwell, 2010; Renn, 2011). Adger et al. (2009, p. 338) argue that many limits to adaptation are dependent on the changing goals, values, risk tolerances, and social choices of society which make them "mutable, subjective, and socially constructed." Similarly, Meze-Hausken (2008) views adaptation as being triggered in part by subjective thresholds including perceptions of change; choices, needs, and values; and expectations about the future (see also O'Brien, 2009). For instance, the distribution of grape suitability will change in response to climate change, but the potential for relocation as an adaptation is limited by the concept of "terroir," which reflects biophysical traits and local knowledge and wine making traditions to a cultural landscape (Box 23-1). However, terroir could become a soft limit if the rigid, regionally defined regulatory frameworks and concepts of regional identity that prescribe what grapes can be grown where were to become more geographically flexible and tied to the culture and history of the winemakers rather than regional climate and grape suitability (Box 23-1).

Limits also have scale-dependent properties (see also Section 16.3.2.10) (*limited evidence*, *high agreement*). Adaptation finance and capacity building activities more broadly, for example, enable resources for adaptation to be transferred from a variety of governmental and non-governmental entities to developing nations in order to overcome soft limits to adaptation (Section 16.3.2.5). For example, a local community may not have the necessary resources to adapt, but these constraints may be overcome by drawing in resources, such as technical expertise, from regional, national, or international authorities as well as from NGOs, other civil society organizations, or the private sector (Section 16.3.2.5). Scale dependence also manifests among different actors within sectoral supply chains. For example, climate change that poses limits to the sustainability of an individual farm enterprise may have less impact on a national or international agribusiness (Park et al., 2012).

16.4.2. Limits and Transformational Adaptation

Adaptation has traditionally been viewed as a process of incremental adjustments to climate variability and change to maintain existing objectives and values despite changes in climate conditions (Smit et al., 2001). As evidenced by the examples in Section 16.4.1, however, future changes in climate could exceed the capacity of human actors and/or natural systems to successfully adapt using incremental adjustments (*medium evidence*, *high agreement*). Since the AR4, the adaptation and resilience literature has suggested that climate change or other factors may drive actors toward the deliberate pursuit of transformational adaptation as a mechanism for managing the discontinuities associated with experiencing an adaptation limit (Pelling, 2010; Kates et al., 2012; O'Brien, 2012; O'Brien et al., 2012; O'Neill and Handmer, 2012; Dow et al., 2013a,b; see also Section 20.3). In addition, some studies have discussed the interactions between incremental and transformational adaptation and the pathways by which actors can transition from one to the other (Pelling, 2010; Park et al., 2012).

As a relatively new concept in the adaptation literature, clear operational definitions of what constitutes transformational adaptation remain elusive. Several authors have offered criteria that include a significant increase in the magnitude of a management effort; introduction of new technologies or practices; formation of new structures or systems of governance; or geographic shifts in the location of activities (Pelling,

2010; Stafford Smith et al., 2011; Kates et al., 2012; O'Neill and Handmer, 2012; Park et al., 2012; see also Sections 20.1, 20.5). However, the concept has also been identified as having normative elements involving changes in desired values, objectives, and perceptions of problems (Pelling, 2010; O'Neill and Handmer, 2012; O'Brien et al., 2012; Park et al., 2012). The current complexity and ambiguity in the definition of transformational adaptation may constrain its effective operationalization in policy environments (*very low confidence*). However, this matter has not been investigated.

In the context of limits to adaptation, transformational adaptation represents options and strategies that human actors can exploit to reorganize systems when incremental adaptation has reached its limits. As with incremental adaptation, these changes can be reactions to what has been experienced in the past or decisions made in anticipation of the future (Kates et al., 2012). As a fundamental change in a system, transformation may involve changes in actors' objectives and associated values. Therefore, transformational adaptation is not without risks or costs (Orlove, 2009; Kates et al., 2012; O'Brien, 2012). For example, the level of investment needed to relocate a community or economic enterprise to reduce the risk of system failure (Kates et al., 2012; O'Neill et al., 2012) and/or to take advantage of changing climatic conditions (Park et al., 2012) may be quite substantial. Furthermore, transformational adaptation may be associated with various externalities. Strategies such as migration, for example, may involve the loss of sense of place and cultural identity, particularly if migration is involuntary (Adger et al., 2009). The feasibility of transformational adaptation may therefore be dependent in part on whether it results in outcomes that are perceived to be positive versus negative (Preston and Stafford Smith, 2009). This suggests that the factors that constrain incremental adaptation (e.g., Section 16.3.2) also can constrain transformation, but the greater level of investment and/or shift in fundamental values and expectations required for transformational change may create greater resistance (*limited evidence*, *medium agreement*; Pelling, 2010; O'Brien, 2012; O'Neill and Handmer, 2012; Park et al., 2012).

16.5. Sectoral and Regional Synthesis

The adaptation literature since the AR4 indicates that despite a range of opportunities to enable adaptation, multiple factors will constrain adaptation planning and implementation (*very high confidence*; see Section 16.3), and, in some cases, such constraints may limit adaptation (*medium evidence*, *high agreement*; see Section 16.4). However, adaptation opportunities, constraints, and limits for adaptation vary significantly among different sectors and regional contexts (*very high confidence*; Adger et al., 2007; see also Sections 16.3-4; Table 16-3). This heterogeneity arises from a range of sources including regional differences with respect to the rate and magnitude of climate change that is experienced, differential exposure and sensitivity of sectors or ecological systems, and differential capacity to adapt. Given this diversity, it is important that opportunities, constraints, and limits are evaluated in the specific context in which they arise. Therefore, this section draws on the various assessments of adaptation presented in the sectoral (Chapters 3 to 13) and regional (Chapters 22 to 30) chapters of the WGII AR5 to synthesize knowledge regarding opportunities, constraints, and limits across these contexts.

16.5.1. Sectoral Synthesis

Each of the sectoral chapters in the WGII AR5 addresses the opportunities for, and constraints associated with, the pursuit of adaptation (Table 16-3). Collectively, this represents a rich body of knowledge regarding how adaptation processes are evolving among different human and natural systems. Although each sectoral chapter assesses the relevant literature on adaptation independently, common themes emerge (Table 16-3). Opportunities most often cited include building awareness, strengthening adaptive capacity, developing tools for improving vulnerability and risk assessments, and adopting favorable policies to improve governance. Likewise, common constraints arise among different sectors, but the bulk of the evidence for adaptation constraints is focused on inadequate governance and institutional structures at the scale of the challenge, lack of access to financial resources or relevant information for adaptation, and social and cultural norms that prevent adoption of viable adaptation options.

There are a number of emerging, integrated approaches to adaptation planning, governance, and implementation identified by many sectoral and regional chapters. For example, Integrated Water Resource Management (IWRM), Integrated Coastal Zone Management (ICZM), Community-Based Adaptation, and Ecosystem-Based Adaptation (EBA) are identified as cross-sectoral adaptation options, which are viewed as more effective than standalone efforts to reduce climate-related risks (Bijlsma et al., 1996; see also Sections 5.5.4, 14.3.2; Box CC-EA). Such integration is important, as many sectors experience threats not only from climate change, but also from a range of existing or emerging threats. The sectoral chapters also reflect on the distinction between autonomous adaptation, which is particularly important for natural systems such as freshwater, coastal, terrestrial, and ocean ecosystems (e.g., WGII AR5 Chapters 3 to 6), and planned adaptation, which features strongly in the literature associated with human-managed systems (WGII AR5 Chapters 5, 7 to 13).

Though the sectoral chapters offer few explicit definitions of adaptation limits, they reflect the potential for hard limits to be reached and the potential for them to be persistent due to interactions among multiple constraints (Section 16.3.2). For example, the sustainability of individual species or ecosystems may experience hard limits in a changing climate, as may ecosystem services for humans such as food crop and fisheries production. Though significantly more attention is given to sectoral adaptation opportunities, constraints, and limits than in the AR4, the AR5 chapters suggest that literature relevant to the coastal (Chapter 5), food systems (Chapter 7), and urban sectors (Chapter 8) has expanded more rapidly, perhaps because of the experience within these sectors with risk reduction planning associated with extreme weather events.

16.5.2. Regional Synthesis

While the regional chapters assess the relevant literature on key sectors affected by climate change, those discussions are specific to the various regional contexts (Table 16-3). Mainstreaming adaptation to climate change into national development policies, regional and local planning, and economic development has emerged as an opportunity across all regions for addressing multiple, interacting stresses (Dovers and Hezri,

Table 16-3 | Sectoral and regional synthesis of adaptation opportunities, constraints, and limits. Each icon represents types of opportunities, constraints, and limits (described below). The size of the icon represents when there is relatively little (small icon) or relatively ample (large icon) information in the sectoral and regional chapters to describe each type of opportunity, constraint, or limit. If no information was presented, the table cell is blank.

Opportunities *are defined as factors that make it easier to plan and implement adaptation actions, that expand adaptation options, or that provide ancillary co-benefits*. Types of opportunities include (1) **Awareness**: communication, education, and awareness raising; (2) **Capacity**: human and institutional capacity building including preparedness, resource provision, and development of human and social capital; (3) **Tools**: decision making, vulnerability and risk analysis, decision support, and early warning tools; (4) **Policy**: integration and mainstreaming of policy, governance, and planning processes including sustainable development, resource and infrastructure planning, and design standards; (5) **Learning**: mutual experiential learning and knowledge management of climate vulnerability, adaptation options, disaster risk response, monitoring, and evaluation; and (6) **Innovation**: development and dissemination of new information, technology development, and technology application.

Constraints *are defined as factors that make it harder to plan and implement adaptation actions*. Types of constraints include (1) **Economic**: existing livelihoods, economic structures, and economic mobility; (2) **Social/cultural**: social norms, identity, place attachment, beliefs, worldviews, values, awareness, education, social justice, and social support; (3) **Human capacity**: individual, organizational, and societal capabilities to set and achieve adaptation objectives over time including training, education, and skill development; (4) **Governance**, Institutions & Policy: existing laws, regulations, procedural requirements, governance scope, effectiveness, institutional arrangements, adaptive capacity, and absorption capacity; (5) Financial: lack of financial resources; (6) **Information**/Awareness/Technology: lack of awareness or access to information or technology; (7) **Physical**: presence of physical barriers; and (8) **Biological**: temperature, precipitation, salinity, acidity, and intensity and frequency of extreme events including storms, drought, and wind.

A ***Limit*** *is defined as the point at which an actor's objectives or system's needs cannot be secured from intolerable risks through adaptive actions*. Types of limits include (1) **Biophysical**: temperature, precipitation, salinity, acidity, and intensity and frequency of extreme events including storms, drought, and wind; (2) **Economic**: existing livelihoods, economic structures and economic mobility; and (3) **Social/cultural**: social norms, identity, place attachment, beliefs, worldviews, values, awareness, education, social justice, and social support.

Sectors

Sectors (chapter)	Opportunities	Constraints	Limits
Freshwater (3)			
Terrestrial (4)			
Coastal (5)			
Ocean systems (6)			
Food systems (7)			
Urban areas (8)			
Rural areas (9)			
Human health (11)			
Human security (12)			

Regions

Regions (chapter)	Opportunities	Constraints	Limits
Africa (22)			
Europe (23)			
Asia (24)			
Australasia (25)			
North America (26)			
Cental & South America (27)			
Polar regions (28)			
Small islands (29)			
Open oceans (30)			

Icon legend

Awareness, Capacity, Tools, Policy, Learning, Innovation, Economic, Human capacity, Social/ cultural, Governance, Financial, Information, Physical, Biological, Biophysical

2010; Tompkins et al., 2010; Table 16-3). Most regional chapters reveal there are significant spatial and temporal mismatches between national adaptation planning on adaptation and local implementation to achieve substantive reductions in vulnerability. Adaptation interventions largely emphasize short-term risk management over long-term transformative strategic planning to reduce long-term risk, which potentially increases vulnerability and therefore the costs associated with future adaption efforts. Such short-sighted decision making can also create the potential for maladaptation (Barnett and O'Neill, 2010; Berrang-Ford et al., 2011; Preston et al., 2013b).

Effective governance and institutions for facilitating adaptation planning and implementation across multiple sectors within regions was by far the dominant opportunity and constraint. Both a shift to risk-based approaches to adaptation and to the multi-sector planning for adaptation mentioned previously (EBA, IRWM, and ICZM) offers opportunities for the development of approaches, tools, and guidelines for the construction of adaptation plans at a regional scale with a long-term focus. Developing and developed nations alike identified opportunities for building adaptive capacity and access to better information at the scale of decision making as important to making this happen. Compared with sectoral chapters, the regional chapters identified limits to adaptation less frequently (Table 16-3). This reflects the tendency for the literature to focus on limits for specific sectors, species, or ecosystems.

16.6. Effects of Mitigation on Adaptation Opportunities, Constraints, and Limits

The AR4 identified four ways in which adaptation and mitigation can interrelate, one of which is mitigation actions that have consequences for adaptation (Klein et al., 2007). It follows that mitigation actions could have consequences for adaptation constraints and limits. Klein et al. (2007) concluded that without mitigation, a magnitude of climate change could be reached that makes adaptation impossible for some natural systems, while for most human systems such high magnitudes of change would involve very high social and economic costs. Adaptation constraints and limits therefore have implications for the definition of dangerous anthropogenic interference under Article II of the UNFCCC (UNFCCC, 1992; see also Travis, 2010; Hoegh-Guldberg, 2011; Tao et al., 2011; Preston et al., 2013a). A number of studies published since the AR4, for example, demonstrate that constraining future greenhouse gas emissions would lower the magnitude of climate change experienced over the 20th century and constrain the magnitude of future adverse impacts or the likelihood of exceeding system thresholds (*very high confidence*; Stern et al., 2006; Preston and Jones, 2008; Sheehan et al., 2008; Meinshausen et al., 2009; O'Neill et al., 2010; Garnaut, 2011; Arnell et al., 2011; Rogelj et al., 2011; Webster et al., 2011; see also discussion of mitigation in the AR5 WGII sectoral and regional chapters). Therefore, mitigation can potentially reduce the magnitude of climate change to which human and natural systems must adapt.

Understanding the relationship between damages avoided by mitigation and adaptation limits requires information regarding what magnitude of climate change and associated damages would constitute an intolerable risk. The WGI contribution to AR5 quantifies the cumulative carbon dioxide (CO_2) emissions below which—with probabilities of >33%, >50%, and >66%—global mean warming would be limited to less than 2°C since the period 1861–1880 (see WGI AR5 Section12.5.4). Warming beyond 2°C is considered to give rise to "reasons for concern" (Smith et al., 2009a; see also Section 19.6), in part because adaptation to impacts associated with such warming would be constrained or limited (Sections 16.3.2, 16.4.1; Box 16-3). Uncertainty about the location of both hard and soft limits is due to the fact that these limits are determined not only by the degree and rate of climate change (as a function of mitigation pathways), but also by the degree and rate of non-climatic stresses affecting the resilience or adaptive capacity of natural and human systems (Section 16.4). Little empirical information is available on the functional relationships between climate change, non-climatic stresses, and the emergence of limits to adaptation. The literature aiming to establish at which degree and rate of climate change, or at which levels of mitigation, such adaptation constraints and limits emerge is sparse and refers primarily to natural systems (*limited evidence*, *medium agreement*; Section 16.4).

Frequently Asked Questions

FAQ 16.3 | How does greenhouse gas mitigation influence the risk of exceeding adaptation limits?

There is *very high confidence* that higher rates and/or magnitudes of climate change contribute to higher adaptation costs and/or the reduced effectiveness of certain adaptation options. For example, increases in global mean temperature of 4°C or more would necessitate greater investment in adaptation than a temperature increase of 2°C or less. As future climate change is dependent on emissions of greenhouse gases, efforts to mitigate those emissions can reduce the likelihood that human or natural systems will experience a limit to adaptation. However, uncertainties regarding how future emissions translate into climate change at global and regional levels remain significant, and therefore it is difficult to draw robust conclusions regarding whether a particular greenhouse gas stabilization pathway would or would not allow residual risk to be successfully managed through adaptation. For example, evidence regarding limits to adaptation does not substantiate or refute the idea that an increase in global mean temperature beyond 2°C represents an adaptation limit or, subsequently, "dangerous anthropogenic interference" as defined by the UNFCCC's Article II.

Nevertheless, studies indicating that limits to adaptation have already been reached for some systems suggest the climate change observed to date has been sufficient to threaten the sustainability of human communities, ecosystem services, or ecological systems (*limited evidence*, *medium agreement*; Section 16.4). For many valued human and natural systems, the complex spatial and temporal dynamics of impacts, adaptive capacity, and adaptation make it difficult to quantitatively project with any degree of accuracy and confidence when and where limits to adaptation will be encountered. Furthermore, although constraints and limits have been demonstrated to have cross-scale and cross-level interactions (Sections 16.3.2.10, 16.4.1), there is little evidence that indicates how limits to adaptation experienced by actors, species, or ecosystems in individual regions or sectors scale to a global aggregate limit. Therefore, there is little evidence to either substantiate or refute the idea that global mean warming beyond 2°C represents a global adaptation limit.

Analysis by Christensen et al. (2011) (see also WGI AR5 Section 12.4.1) shows that all emission scenarios—whether aggressive mitigation scenarios consistent with a 2°C stabilization pathway or medium-high emission scenarios such as *Special Report on Emission Scenarios* (SRES) A1B and A1Fi, or Representative Concentration Pathway 6.0 (RCP6.0) and RCP8.5—are very similar in terms of projected climate up to 2040 (i.e., the "era of climate responsibility"). The effects of mitigation on overall adaptation potential will therefore arise in the medium to long term, during the "era of climate options." Integrated Assessment Models (IAMs) can assess the relative damage-reducing effect of mitigation and adaptation, based on the assumption that the two strategies are substitutes. In reality, however, mitigation and adaptation are hardly substitutable: they create benefits on different spatial, institutional and temporal scales and involve different actors with different interests. Substitutability of mitigation and adaptation in IAMs requires the reconciliation of welfare impacts on people living in different places and at different points in time into an aggregate measure of well-being (Klein et al., 2007). Moreover, defining the costs and benefits of adaptation is particularly difficult, limited by data, and depends on value judgments (Chapter 17).

Since AR4 the literature on tipping elements (Lenton et al., 2008; Kriegler et al., 2009; Levermann et al., 2012) has provided a greater separation of mitigation and adaptation, because only mitigation can avoid these discontinuities. While there could be potential for mitigation and adaptation substitutability under scenarios where catastrophic climate change is avoided, the thresholds for the onset of any tipping elements (anticipated to drive some systems to the limits of adaptation) are not known. These concerns have been picked up in the economic literature, in relation to the plausible, if unknown, probability of catastrophic climate change as well as "fat tails," where uncertainty is so large that the tails of the probability distribution tend to dominate (Weitzman, 2009). Against this background, mitigation can prevent or delay catastrophic climate change and the reaching of adaptation limits.

Several studies using IAMs have investigated tradeoffs between mitigation and adaptation (de Bruin et al., 2009a; Bosello et al., 2010), treating the two strategies as substitutes in order to find a balance or even an optimal mix. De Bruin et al. (2009a) report that short-term optimal policies need to consist of a mixture of substantial investments in adaptation measures, coupled with investments in mitigation, even though the latter will decrease damages only in the longer term. They also find that the relative mix of the two depends critically on the assumptions, notably in relation to discount rate and the parameterization of damages. Felgenhauer and de Bruin (2009) examine the role that uncertainty over climate sensitivity has on optimal mitigation and adaptation policy levels over time. They find that optimal levels of both mitigation and adaptation are lower under uncertainty than under certainty, and that the optimal mitigation level is more dependent on adaptation costs than vice versa.

Such findings are all preliminary, because the current representation of adaptation in IAMs is generally very simple (Ackerman et al., 2009; Patt et al., 2010b). The models adopt a highly aggregated and theoretical approach without considering any real-world constraints on adaptation (Ackerman et al., 2009; Patt et al., 2010b). They also often assume perfect foresight, no uncertainty, and no maladaptation (see also Watkiss, 2011; Berkhout, 2012). More recent models have attempted to address some of these issues. De Bruin and Dellink (2011), for example, model different types of constraints of adaptation over time. Also the PAGE09 model assumes adaptation to be about half as effective as it was in PAGE02 (Hope, 2011). Along with other factors, the reduced effectiveness of adaptation in the model leads to a strong increase in the economic costs of climate change (Hope, 2011).

16.7. Ethical Dimensions of Adaptation Opportunities, Constraints, and Limits

Hartzell-Nichols (2011, p. 690) argues that, in general terms, "Adaptation is fundamentally an ethical issue because the aim of adaptation is to protect that which we value." More specifically, ethical issues concern the distribution of costs and benefits of prevention measures and adaptation activities, compensation for residual damages, and participation in the related decision processes (Grasso, 2009). These distributive and procedural justice-related issues can be diverse and contextually specific (Paavola, 2011). Brisley et al. (2012) argue that ensuring social justice in adaptation requires both an understanding of which groups are most vulnerable to climate change impacts, as well as social choice processes about adaptation responses that are seen to meet the needs of the vulnerable fairly. The key ethical issues raised by adaptation opportunities, constraints, and limits as they are discussed here are summarized in Table 16-4, together with the public policy questions they raise.

Defining general moral principles to clarify how to handle risks to objectives, values, and needs, including where they are unavoidable and catastrophic, is difficult. According to Gardiner (2006, p. 407), "Even our best theories face basic and often severe difficulties addressing basic issues … such as scientific uncertainty, intergenerational equity, contingent persons, nonhuman animals, and nature. But climate change involves all of these matters and more."

Complicating this picture further is the observation that social and personal values are not universal or static (O'Brien, 2009; O'Brien and Wolf, 2010). There may be different, but equally legitimate, values that are fostered or put at risk by climate change (Adger et al., 2012). These are not limited to instrumental or economic values, but include cultural

Table 16-4 | Ethical dimensions of adaptation opportunities, constraints, and limits and their policy implications.

	Ethical dimensions	Commentary	Public policy issues	References
Adaptation opportunities	Access to opportunities	Inequitable access to the factors that make it easier to adapt and achieve adaptation objectives	Whether national or international policy should support more equitable access to adaptation opportunities	Thomas and Twyman (2005); Paavola and Adger (2006); Paavola (2008); Füssel (2010); Rübbelke (2011); Klinsky et al. (2012)
Adaptation constraints	Distribution of constraints	Inequitable distribution of factors that make it harder to plan and implement adaptation actions	Whether national or international policy should reduce or remove constraints to adaptation	Paavola and Adger (2006); Klein and Möhner (2009); Grasso (2010)
Adaptation limits	Differing attitudes to risk	What is deemed an acceptable, tolerable, and intolerable risk will vary across cultures, social groups, and individuals.	Risk governance is concerned with balancing differentiated and dynamic attitudes to risk in allocating resources to managing risks.	Bisaro et al. (2010); Juhola et al. (2011); Lata and Nunn (2012); Sovacool (2012); Fatti and Patel (2013); Ward et al. (2013)
	Rights and potentials of people to secure particular valued objectives	Limits are related to given valued objectives, but such objectives vary between individuals and collectives.	Risk governance related to adaptation limits is concerned with setting priorities between different (and conflicting) valued objectives.	Foale (2008); Devine-Wright (2009); Gorman-Murray (2010); Jacob et al. (2010); Brown et al. (2011); Adger et al. (2012)
	Differing rates at which limits are reached	Limits will be reached earlier by some groups and regions (Arctic, unprotected coastal zones) than others.	Risk governance at different scales will be confronted with choices about adaptation limits emerging through time.	Baum and Easterling (2010); Edvardsson-Bjornberg and Hansson (2011); Dow et al. (2013a)
	Trade-offs in securing valued objectives	Adaptive responses will involve choices between valued objectives at adaptation limits (i.e., between river water quality and water demand from irrigation).	As adaptation limits that affect multiple valued objectives are reached, private and public choices will be made about which values have priority over others.	Steenberg et al. (2011); Towler et al. (2012); Pittock (2013); Seidl and Lexer (2013)
	Intergenerational and interspecies equity and adaptation limits	Valued objectives may be irrecoverably lost at adaptation limits, denying them to future generations.	Species extinctions and loss of cultural heritage, place, or identity may call for extraordinary public policy interventions.	Albrecht et al. (2013)

values as well. Berkes (2008, p. 163), for instance, documents that in Inuit culture, the loss of sea ice in summer months leaves some people "lonely for the ice." Whether the risk of irreversible cultural losses would be seen as intolerable remains a complicated question, but has been noted to manifest in a psychological response termed "solastalgia" (Albrecht et al., 2007). The loss of traditional ways of experiencing and seeing the world is a common occurrence throughout human history. The ethical question is whether such losses should be acknowledged in considering adaptation opportunities, constraints, and limits (as well as in human responses to climate change more generally).

One ethical principle that is widely applied in ethical discussions of climate is "equity" (Gardiner, 2010). It is now well established that nations, peoples, and ecosystems are differentially vulnerable to current and future projected climate change impacts, which themselves are unequally distributed across world regions (*very high confidence*; IPCC, 2007b; Füssel, 2009, 2010). This inequity is exacerbated by the fact that exposure to adverse impacts is involuntary for many societies (Paavola and Adger, 2006; Patz et al., 2007; Dellink et al., 2009; Füssel, 2010). Thus, adaptation constraints have the potential to create or exacerbate inequitable consequences due to climate change (*very high confidence*). Where limits to adaptation lead to catastrophic losses there is often a need for humanitarian responses, as well as more structural adaptations at the societal level (*medium evidence*, *high agreement*; Bardsley and Hugo, 2010). Linked to this is the complex question of the attribution of risks to anthropogenic forcing of climate change and whether there could be grounds for redress or compensation (Verheyen, 2005). In this regard, different ethical positions taken by countries such as through "equity weighting" would result in very different compensation outcomes (Anthoff and Tol, 2010).

Inequity resulting from adaptation constraints and limits emerge across several dimensions: inter-country equity, inter-generational equity, inter-species equity (Schneider and Lane, 2006b), and intra-country or sub-national equity (Thomas and Twyman, 2005). Climate change, and the need for adaptation, unfairly shifts burdens onto future generations, contradicting the principle of intergenerational equity. This raises ethical and justice questions because benefits are extracted from the global environment by those who do not bear the burden of that extraction (UNEP, 2007). Policy debates about intergenerational equity considerations have been dominated by the need to treat the time discount rate consistently across cases (Nordhaus, 2001; Stern et al., 2006; Beckerman and Hepburn, 2007). But this debate largely ignores the challenge of irreversible damages associated with limits to adaptation, especially those that may result from nonlinear damage functions (Hanemann, 2008). Inter-species equity is the subject of an evolving ethics debate (e.g., Jolibert et al., 2011), but adaptation interventions involving ecosystems and wild species increasingly invoke human and societal benefits as a primary motivation (CBD, 2009; Box CC-EA).

Law codifies the social values and objectives influenced by opportunities, constraints, and limits to adaptation, and sets norms and procedures for dealing with problems of risk and loss, including the intolerable losses experienced at adaptation limits (Section 16.3.2.8). Changing such values and objectives, including the shifting and sharing of risks this may involve, will often involve complex and time-consuming governance effort. National and international law will play a role in managing and sharing climate-related risks. The Cancun Adaptation Framework (UNFCCC, 2011) adopted at COP16 of the UNFCCC sets out principles for international cooperation on adaptation "…to enable and support the implementation of adaptation actions" (UNFCCC, 2010,

p. 4). Nevertheless, the complexity of international law comprises a significant constraint to making the case for addressing the breaching of adaptation limits (Koivurova, 2007). At national and subnational levels, cultural attitudes can contribute to stakeholder marginalization from adaptation processes (Section 16.3.2.7), thus preventing some constraints and limits from being identified (such as gender issues and patriarchal conventions).

16.8. Seizing Opportunities, Overcoming Constraints, and Avoiding Limits

As discussed in this chapter, researchers and practitioners now have a richer understanding of how constraints and limits influence adaptation (Sections 16.3-7). Based on the available literature, however, less attention has been paid to understanding the range of opportunities that exist and how they create enabling conditions for adaptation (Section 16.3.1; Table 16-1). Focused research on facilitating such enabling conditions and how these lead to the minimization or avoidance of adaptation constraints would support capacity building of individuals and institutions (*very high confidence*; Smith et al., 2008; Ford, 2009; Burch, 2010; Ford et al., 2010; Eisenack, 2012; Biesbroek et al., 2013a). Translating knowledge of potential opportunities into adaptation responses requires that they be recognized and then exploited by actors. Such opportunities are being created through policies, tools, and guidelines that are emerging throughout the developed and developing world (Sections 15.2, 16.3.2.1). It is not yet clear if these efforts are translating into effective adaptation actions for the benefit of human and natural systems including the avoidance of limits. As adaptation practice has focused on what adaptation efforts can achieve in terms of avoided damages rather than on the residual damages that adaptation cannot avoid (Jenkins et al., 2011; McNamara et al., 2011), this question remains largely unexplored.

Adaptation constraints have contributed to uneven adaptation planning and implementation, with some sectoral and regional actors progressing more rapidly than others (*very high confidence*; Urwin et al., 2008; Biesbroek et al., 2010; Tompkins et al., 2010; Bichard and Kazmierczak, 2012; Bierbaum et al., 2012; Carmin et al., 2012). Multiple studies have concluded that adaptation is largely proceeding autonomously and incrementally, often in response to perceived climate change trends and impacts that have been experienced (*medium evidence*, *high agreement*; Ford, 2009; Ford et al., 2010, 2011; Berrang-Ford et al., 2011; Preston et al., 2011a; Lesnikowski et al., 2013). In so doing, however, actors may not adequately invest in adaptation responses that will address future long-term risks associated with higher levels of climate change (*limited evidence*, *medium agreement*; Preston et al., 2013b; see also Section 16.3.2.2). The suggestion that incremental approaches to mitigation and adaptation may be inadequate to avoid intolerable risks has led to a growing discourse regarding transformational adaptation (Pelling, 2010; Kates et al., 2012; O'Brien, 2012; O'Neill and Handmer, 2012; Park et al., 2012). While various practical examples of transformational adaptation appear in the literature (Kates et al., 2012; O'Neill and Handmer, 2012; Park et al., 2012; see also Section 16.4.2), the extent to which transformational adaptation can be operationalized within adaptation policy remains unclear. Unresolved issues including which actors, sectors, and regions should be considering transformational adaptations, when, and what constitutes appropriate adaptation actions under such circumstances would benefit from focused investigation.

Better understanding and quantification of how future GHG emissions trajectories and climate change translates into impacts would improve understanding of limits to adaptation. Fundamental understanding of the vulnerability of different regions and sectors to climate change suggest that adaptive capacity is finite and thus, in general, limits to adaptation can be anticipated to arise as a consequence of future global change (*medium evidence*, *high agreement*; Sections 16.3.2, 16.4-6). Yet, at present, understanding of limits to adaptation is largely qualitative, and it is unclear whether current approaches to assessing climate change impacts and adaptation sufficiently explore the range of potential future climates and adaptive capacities of human and natural systems in a manner that is sufficient to identify limits. The parallel process for scenario development may provide a coherent framework for internally consistent analyses of climate change impacts that address uncertainty among climate models, emissions scenarios, and socioeconomic scenarios (Moss et al., 2010; van Vuuren et al., 2012; Ebi et al., 2013). Such knowledge could subsequently provide early warning of systems at risk of experiencing intolerable risks (Dow et al., 2013a,b) while also providing guidance regarding GHG mitigation targets.

Finally, recent literature questions whether existing institutions and systems of governance are adequate to effectively manage climate change risk. This includes not only institutions engaging in adaptation planning and implementation (Berkes and Armitage, 2010; Chapin et al., 2010; National Research Council, 2010; UKCIP, 2011; Kates et al., 2012; Biesbroek et al., 2013a), but also those associated with adaptation research (Meyer, 2011; Kates et al., 2012). New institutions and institutional arrangements have in fact emerged including adaptation research institutions with boundary spanning functions (Preston et al., 2013c; see also Section14.2.3), as well as those designed to facilitate adaptation and improve environmental and risk management (*medium evidence*, *high agreement*; National Research Council, 2009; Biesbroek et al., 2011; Jäger and Moll, 2011; Lemos et al., 2013). However, others have cautioned that the complexity of modern governance systems poses significant constraints on institutional change (Adger et al., 2009; see also Section 16.3.2.8), and new institutions do not necessarily resolve complex governance challenges (Lebel et al., 2013). Additional research is therefore needed regarding the extent to which new institutions will be required to effectively govern adaptation.

References

Aaheim, A., H. Amundsen, T. Dokken, and T. Wei, 2012: Impacts and adaptation to climate change in European economies. *Global Environmental Change*, **22(4)**, 959-968.

Abbott, P. and A.B. de Battisti, 2011: Recent global food price shocks: causes, consequences and lessons for African governments and donors. *Journal of African Economies*, **20(Suppl. 1)**, 12-62.

Abel, N., R. Gorddard, B. Harman, A. Leitch, J. Langridge, A. Ryan, and S. Heyenga, 2011: Sea level rise, coastal development and planned retreat: analytical framework, governance principles and an Australian case study. *Environmental Science & Policy*, **14(3)**, 279-288.

Acheson, J.M., 2006: Institutional failure in resource management. *Annual Review of Anthropology*, **35**, 117-134.

Ackerman, F., S.J. DeCanio, R.B. Howarth, and K. Sheeran, 2009: Limitations of integrated assessment models of climate change. *Climatic Change*, **95(3-4)**, 297-315.

Adaptation Fund Board, 2013: *Adaptation Fund Trust Fund: Financial Report Prepared by the Trustee*. AFB/EFC.12/8, Ethics and Finance Committee, Thirteenth Meeting, Adaptation Fund Board, Bonn, Germany, 15 pp.

Adaptation Sub-Committee, 2012: *Climate Change: Is the UK Preparing for Flooding and Water Scarcity?* Adaptation Sub-Committee Progress Report, Committee on Climate Change, London, UK, 51 pp.

Adger, W.N., 2010: Social capital, collective action, and adaptation to climate change. In: *Der Klimawandel* [Voss, M. (ed.)]. VS Verlag für Sozialwissenschaften, Dordrecht, Netherlands, pp. 327-345.

Adger, W.N. and J. Barnett, 2009: Four reasons for concern about adaptation to climate change. *Environment and Planning A*, **41(12)**, 2800-2805.

Adger, W.N., S. Agrawala, M.M.Q. Mirza, C. Conde, K. O'Brien, J. Pulhin, R. Pulwart, B. Smit, and K. Takahashi, 2007: Assessment of adaptation practices, options, constraints and capacity. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 717-743.

Adger, W.N., H. Eakin, and A. Winkels, 2008: Nested and teleconnected vulnerabilities to environmental change. *Frontiers in Ecology and the Environment*, **7(3)**, 150-157.

Adger, W.N., S. Dessai, M. Goulden, M. Hulme, I. Lorenzoni, D.R. Nelson, L.O. Naess, J. Wolf, and A. Wreford, 2009: Are there social limits to adaptation to climate change? *Climatic Change*, **93(3-4)**, 335-354.

Adger, W.N., J. Barnett, F.S. Chapin, and H. Ellemor, 2011: This must be the place: underrepresentation of identity and meaning in climate change decision-making. *Global Environmental Politics*, **11(2)**, 1-25.

Adger, W.N., J. Barnett, K. Brown, N.A. Marshall, and K. O'Brien, 2012: Cultural dimensions of climate change impacts and adaptation. *Nature Climate Change*, **3**, 112-117.

Adger, W.N., T. Quinn, I. Lorenzoni, C. Murphy, and J. Sweeney, 2013: Changing social contracts in climate-change adaptation. *Nature Climate Change*, **3(4)**, 330-333.

Afreen, S., N. Sharma, R.K. Chaturvedi, R. Gopalakrishnan and N.H. Ravidranath, 2011: Forest policies and programs affecting vulnerability and adaptation to climate change. *Mitigation and Adaptation Strategies for Global Change*, **16(2)**, 177-197.

Agrawala, S., 2005: Putting climate change in the development mainstream: introduction and framework. In: *Bridge Over Troubled Waters: Linking Climate Change and Development* [Agrawala, S. (ed.)]. Organisation for Economic Co-operation and Development (OECD), Paris, France, pp. 23-43.

Ahmed, S. and E. Fajber, 2009: Engendering adaptation to climate variability in Gujarat, India. *Gender & Development*, **17(1)**, 33-50.

Aitken, S.N., S. Yeaman, J.A. Holliday, T. Wang, and S. Curtis-McLane, 2008: Adaptation, migration or extirpation: climate change outcomes for tree populations. *Evolutionary Applications*, **1(1)**, 95-111.

Aitken, S.N., S. Yeaman, E.J. Eliason, T.D. Clark, M.J. Hague, L.M. Hanson, Z.S. Gallagher, K.M. Jeffries, and A.P. Farrell, 2011: Differences in thermal tolerance among sockeye salmon populations. *Science*, **332(6025)**, 109-112.

Alberti, M., 2010: Maintaining ecological integrity and sustaining ecosystem function in urban areas. *Current Opinion in Environmental Sustainability*, **2**, 178-184.

Albrecht, G., G.-M. Sartore, L. Conner, N. Higginbotham, S. Freeman, B. Kelly, H. Stain, A. Tonna, and G. Pollard, 2007: Solastalgia: the distress caused by environmental change. *Australasian Psychiatry*, **15(Suppl. 1)**, S95-S98.

Albrecht, G.A., C. Brooke, D.H. Bennett, and S.T. Garnett, 2013: The ethics of assisted colonization in the age of anthropogenic climate change. *Journal of Agricultural and Environmental Ethics*, **26(4)**, 827-845.

Alcamo, J., J.M. Moreno, B. Nováky, M. Bindi, R. Corobov, R.J.N. Devoy, C. Giannakopoulos, E. Martin, J.E. Olesen, and A. Shvidenko, 2007: Europe. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 541-580.

Ali, A., 1999: Climate change impacts and adaptation assessment in Bangladesh. *Climate Research*, **12**, 109-116.

Allison, E.H., A.L. Perry, M.C. Badjeck, N. Adger, K. Brown, D. Conway, and N.K. Dulvy, 2009: Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries*, **10(2)**, 173-196.

Almansi, F., 2009: Regularizing land tenure within upgrading programmes in Argentina; the cases of Promeba and Rosario Hábitat. *Environment and Urbanization*, **21(2)**, 389-413.

Alston, M. and R. Mason, 2008: Who turns the taps off? Introducing social flow to the Australian water debate. *Rural Society*, **18(2)**, 131-139.

Amaru, S. and N.B. Chhetri, 2013: Climate adaptation: Institutional response to environmental constraints, and the need for increased flexibility, participation, and integration of approaches. *Applied Geography*, **39**, 128-139.

Anisimov, O.A., D.G. Vaughan, T.V. Callaghan, C. Furgal, H. Marchant, T.D. Prowse, H. Vilhjálmsson, and J.E. Walsh, 2007: Polar regions (Artic and Antarctica). In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 653-685.

Anthoff, D. and R.S. Tol, 2010: On international equity weights and national decision making on climate change. *Journal of Environmental Economics and Management*, **60(1)**, 14-20.

Anwar, M.R., D. Li Liu, I. Macadam, and G. Kelly, 2013: Adapting agriculture to climate change: a review. *Theoretical and Applied Climatology*, **113(1-2)**, 225-245.

Aporta, C. and E. Higgs, 2005: Satellite culture: global positioning systems, Inuit wayfinding, and the need for a new account of technology. *Current Anthropology*, **46**, 729-753.

Armour, K.C. and G.H. Roe, 2011: Climate commitment in an uncertain world. *Geophysical Research Letters*, **38(1)**, L01707, doi:10.1029/2010GL045850.

Arnell, N.W., D.P. van Vuuren, and M. Isaac, 2011: The implications of climate policy for the impacts of climate change on global water resources. *Global Environmental Change*, **21(2)**, 592-603.

Artur, L. and D. Hilhorst, 2012: Everyday realities of climate change adaptation in Mozambique. *Global Environmental Change*, **22(2)**, 529-536.

Ayers, J., 2009: International funding to support urban adaptation to climate change, *Environment and Urbanization*, **21(1)**, 225-240

Ayers, J. and S. Huq, 2009: Supporting adaptation to climate change: what role for official development assistance? *Development Policy Review*, **27(6)**, 675-692.

Badjeck, M.C., E.H. Allison, A.S. Halls, and N.K. Dulvy, 2010: Impacts of climate variability and change on fishery-based livelihoods. *Marine Policy*, **34(3)**, 375-383.

Baldassarre, G., A. Montanari, H. Lins, D. Koutsoyiannis, L. Brandimarte, and G. Blöschl, 2010: Flood fatalities in Africa: from diagnosis to mitigation. *Geophysical Research Letters*, **37(22)**, L22402, doi:10.1029/2010GL045467.

Bangay, C. and N. Blum, 2012: Education responses to climate change and quality: two parts of the same agenda? *International Journal of Educational Development*, **30(4)**, 359-368.

Bardsley, D.K. and G.J. Hugo, 2010: Migration and climate change: examining thresholds of change to guide effective adaptation decision-making. *Population and Environment*, **32**, 238-262.

Bark, R.H., B.G. Colby, and F. Dominguez, 2010: Snow days? Snowmaking adaptation and the future of low latitude, high elevation skiing in Arizona, USA. *Climatic Change*, **102(3-4)**, 467-491.

Barr, R., S. Fankhauser, and K. Hamilton, 2010: Adaptation investments: a resource allocation framework. *Mitigation and Adaptation Strategies for Global Change*, **15(8)**, 843-858.

Barnett, J. and J. Campbell, 2009: *Climate Change and Small Island States: Power, Knowledge and the South Pacific.* Earthscan, London, UK, 232 pp.

Barnett, J. and S. O'Neill, 2010: Maladaptation. *Global Environmental Change*, **20**, 211-213.

Barnett, J., S. Lambert, and I. Fry, 2009: The hazards of indicators: insights from the environment vulnerability index. *Annals of the Association of American Geographers*, **98(1)**, 102-119.

Bates, B.C., Z.W. Kundzewicz, S. Wu, and J.P. Palutikof (eds.), 2008: *Climate Change and Water.* Intergovernmental Panel on Climate Change (IPCC) Technical Paper VI, IPCC Secretariat, Geneva, Switzerland, 200 pp.

Baum, S.D. and W.E. Easterling, 2010: Space-time discounting in climate change adaptation. *Mitigation and Adaptation Strategies for Global Change*, **15**, 591-609.

Beard, L.M., J.B. Cardell, I. Dobson, F. Galvan, D. Hawkins, W. Jewell, M. Kezunovic, T.J. Overbye, P.K. Sen, and D.J. Tylavsky, 2010: Key technical challenges for the electric power industry and climate change. *IEEE Transactions on Energy Conversion*, **25(2)**, 465-473.

Becker, A., S. Inoue, M. Fischer, and B. Schwegler, 2012: Climate change impacts on international seaports: knowledge, perceptions, and planning efforts among port administrators. *Climatic Change*, **110(1-2)**, 5-29.

Becker, N., D. Lavee, and D. Katz, 2010: Desalination and alternative water-shortage mitigation options in Israel: a comparative cost analysis. *Journal of Water Resource and Protection*, **2**, 1042-1056.

Beckerman, W. and C. Hepburn, 2007: Ethics of the discount rate in the Stern Review on the economics of climate change. *World Economics*, **8(1)**, 187-210.

Begum, R.A. and J.J. Pereira, 2013: The awareness, perception and motivational analysis of climate change and business perspectives in Malaysia. *Mitigation and Adaptation Strategies for Global Change*, link.springer.com/article/10.1007/s11027-013-9495-6.

Benito, B., J. Lorite, and J. Peñas, 2011: Simulating potential effects of climatic warming on altitudinal patterns of key species in Mediterranean-alpine ecosystems. *Climatic Change*, **108(3)**, 471-483.

Berkes, F., 2008: *Sacred Ecology*. Routledge, Abingdon, UK and New York, NY, USA, 363 pp.

Berkes, F. and D. Armitage, 2010: Co-management institutions, knowledge, and learning: adapting to change in the Arctic. *Études/Inuit/Studies*, **34(1)**, 109-131.

Berkhout, F., 2012: Adaptation to climate change by organizations. *Wiley Interdisciplinary Reviews: Climate Change*, **3(1)**, 91-106.

Berkhout, F., J. Hertin, and D. M. Gann, 2006: Learning to adapt: organisational adaptation to climate change impacts. *Climatic Change*, **78(1)**, 135-156.

Bern, C., J. Sniezek, G.M. Mathbor, M.S. Siddiqi, C. Ronsmans, A.M. Chowdhury, and E. Noji, 1993: Risk factors for mortality in the Bangladesh cyclone of 1991. *Bulletin of the World Health Organization*, **71(1)**, 73-78.

Bernazzani, P., B.A. Bradley, and J.J. Opperman, 2012: Integrating climate change into habitat conservation plans under the US Endangered Species Act. *Environmental Management*, **49(6)**, 1103-1114.

Berrang-Ford, L., J.D. Ford, and J. Paterson, 2011: Are we adapting to climate change? *Global Environmental Change*, **21**, 25-33.

Berry, P., K.L. Clarke, M. Pajot, and D. Hutton, 2011: Chapter 14: Risk perception, health communication, and adaptation to the health impacts of climate change in Canada. In: *Climate Change Adaptation in Developed Nations: From Theory to Practice* [Ford, J.D. and L. Berrang-Ford (eds.)]. Advances in Global Change Research Series, Vol. 42, Springer, New York, NY, USA, pp. 205-219.

Bichard, E. and A. Kazmierczak, 2012: Are homeowners willing to adapt to and mitigate the effects of climate change? *Climatic Change*, **112(3-4)**, 633-654.

Bierbaum, R., J.B. Smith, A. Lee, M. Blair, L. Carter, F.S. Chapin III, P. Fleming, S. Ruffo, M. Stults, S. McNeeley, E. Wasley, and L. Verduzco, 2013: A comprehensive review of climate adaptation in the United States: more than before, but less than needed. *Mitigation and Adaptation Strategies for Global Change*, **18(3)**, 361-406.

Biesbroek, G.R., R.J. Swart, T.R. Carter, C. Cowan, T. Henrichs, H. Mela, M.D. Morecroft, and D. Rey, 2010: Europe adapts to climate change: comparing national adaptation strategies. *Global Environmental Change*, **20(3)**, 440-450.

Biesbroek, G.R., J. Klostermann, C. Termeer, and P. Kabat, 2011: Barriers to climate change adaptation in the Netherlands. *Climate Law*, **2(2)**, 181-199.

Biesbroek, G.R., J. Klostermann, C. Termeer, and P. Kabat, 2013a: On the nature of barriers to climate change adaptation. *Regional Environmental Change*, **13(5)**, 1119-1129.

Biesbroek, G.R., C.J. Termeer, J.E. Klostermann, and P. Kabat, 2013b: Analytical lenses on barriers in the governance of climate change adaptation. *Mitigation and Adaptation Strategies for Global Change*, doi:10.1007/s11027-013-9457-z.

Bijlsma, L., C.N. Ehler, R.J.T. Klein, S.M. Kulshrestha, R.F. McLean, N. Mimura, R.J. Nicholls, L.A. Nurse, H. Pérez Nieto, E.Z. Stakhiv, R.K. Turner, and R.A. Warrick, 1996: Coastal zones and small islands. In: *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change* [Watson, R.T., M.C. Zinyowera, and R.H. Moss (eds.)]. Cambridge University Press, Cambridge, UK, New York, NY, USA, and Melbourne, Australia, pp. 289-324.

Birkmann, J., M. Garschagen, F. Kraas, and Q. Nguyen, 2010: Adaptive urban governance: new challenges for the second generation of urban adaptation strategies to climate change. *Sustainability Science*, **5(2)**, 185-206.

Bisaro, A., S. Wolf, and J. Hinkel, 2010: Framing climate vulnerability and adaptation at multiple levels: addressing climate risks or institutional barriers in Lesotho? *Climate and Development*, **2(2)**, 161-175.

Blennow, K. and J. Persson, 2009: Climate change: motivation for taking measure to adapt. *Global Environmental Change*, **19(1)**, 100-104.

Bosello, F., C. Carraro, and E. De Cian, 2010: Climate policy and the optimal balance between mitigation, adaptation and unavoided damage. *Climate Change Economics*, **1(02)**, 71-92.

Botzen, W., J. Aerts, and J. van den Bergh, 2009: Willingness of homeowners to mitigate climate risk through insurance. *Ecological Economics*, **68(8-9)**, 2265-2277.

Botzen, W., J. van den Bergh, and L. Bouwer, 2010: Climate change and increased risk for the insurance sector: a global perspective and an assessment for the Netherlands. *Natural Hazards*, **52(3)**, 577-598.

Bourgeon, J., W. Easter, and R. Smith, 2008: Water markets and third-party effects. *American Journal of Agricultural Economics*, **90(4)**, 902-917.

Bouwer, L.M., 2011: Have disaster losses increased due to anthropogenic climate change? *Bulletin of the American Meteorological Society*, **92(1)**, 39-46.

Bouwer, L.M. and J.C. Aerts, 2006: Financing climate change adaptation. *Disasters*, **30(1)**, 49-63.

Bowen, A., S. Cochrane, and S. Fankhauser, 2012: Climate change, adaptation and economic growth. *Climatic Change*, **113(2)**, 95-106.

Boxall, A., A. Hardy, S. Beulke, T. Boucard, L. Burgin, P. Falloon, P. Haygarth, T. Hutchinson, R. Kovats, G. Leonardi, L. Levy, G. Nichols, S. Parsons, L. Potts, D. Stone, E. Topp, D. Turley, K. Walsh, E. Wellington, and R. Williams, 2009: Impacts of climate change on indirect human exposure to pathogens and chemicals from agriculture. *Environmental Health Perspectives*, **117(4)**, 508-514.

Bradshaw, W.E. and C.M. Holzapfel, 2006: Evolutionary response to rapid climate change. *Science*, **312**, 1477-1478.

Breakwell, G.M., 2010: Models of risk construction: some applications to climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **1(6)**, 857-870.

Briske, D.D., R.A. Washington-Allen, C.R. Johnson, J.A. Lockwood, D.R. Lockwood, T.K. Stringham, and H.H. Shugart, 2010: Catastrophic thresholds: a synthesis of concepts, perspectives, and applications. *Ecology and Society*, **15(3)**, 37, www.ecologyandsociety.org/vol15/iss3/art37/.

Brisley, R., J. Welstead, R. Hindle, and J. Paavola, 2012: *Socially Just Adaptation to Climate Change*. Joseph Roundtree Foundation, York, UK, 118 pp.

Brook, B.W., N.S. Sodhi, and J.A. Bradshaw, 2008: Synergies among extinction drivers under global change. *Trends in Ecology & Evolution*, **23(8)**, 453-460.

Brouwer, S., T. Rayner, and D. Huitema, 2013: Mainstreaming climate policy. The case of climate adaptation and the implementation of EU water policy. *Environment and Planning C*, **31(1)**, 134-153.

Brown, D., 2011: Making the linkages between climate change adaptation and spatial planning in Malawi. *Environmental Science & Policy*, **14(8)**, 940-949.

Brown, T., L. Budd, M. Bell, and H. Rendell, 2011: The local impact of global climate change: reporting on landscape transformation and threatened identity in the English regional newspaper press. *Public Understanding of Science*, **20**, 658-673.

Brunsma, D.L., D. Overfelt, and J.S. Picou, 2010: *The Sociology of Katrina: Perspectives on a Modern Catastrophe.* Brown and Littlefield, Lanham, MD, USA, 365 pp.

Bryan, E., T.T. Deressa, G.A. Gbetibouo, and C. Ringler, 2009: Adaptation to climate change in Ethiopia and South Africa: options and constraints. *Environmental Science & Policy*, **12(4)**, 413-426.

Bulkeley, H. and V. Castán Broto, 2012: Government by experiment? Global cities and the governing of climate change. *Transactions of the Institute of British Geographers*, **38(3)**, 361-375.

Buob, S. and G. Stephan, 2013: On the incentive compatibility of funding adaptation. *Climate Change Economics*, **04(2)**, 1350005, doi:10.1142/S2010007813500005X.

Bulleri, F. and M.G. Chapman, 2010: The introduction of coastal infrastructure as a driver of change in marine environments. *Journal of Applied Ecology*, **47**, 26-35.

Burch, S., 2010: Transforming barriers into enablers of action on climate change: insights from three municipal case studies in British Columbia, Canada. *Global Environmental Change*, **20(2)**, 287-297.

Burton, I. 2008: *Beyond Borders: The Need for Strategic Global Adaptation*. Sustainable Development Opinion Series, Policy Briefing December 2008, International Institute for Environment and Development (IIED), London, UK, 2 pp.

Burton, I., O.P. Dube, D. Campbell-Lendrum, I. Davis, R.J.T. Klein, J. Linnerooth-Bayer, A. Sanghi, and F. Toth, 2012: Managing the risks: international level and integration across scales. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 393-435.

Butzer, K.W., 2012: Collapse, environment, and society. *Proceedings of the National Academy of Sciences of the United States of America*, **109(10)**, 3632-3639.

Butzer, K.W. and G.H. Endfield, 2012: Critical perspectives on historical collapse. *Proceedings of the National Academy of Sciences of the United States of America*, **109(10)**, 3628-3631.

Byg, A. and J. Salick, 2009: Local perspectives on a global phenomenon: climate change in Eastern Tibetan villages. *Global Environmental Change*, **19**, 156-166.

Cabral, J.S., F. Jeltsch, W. Thuiller, S. Higgins, G.F. Midgley, A.G. Rebelo, M. Rouget, and F.M. Schurr, 2013: Impacts of past habitat loss and future climate change on the range dynamics of South African Proteaceae. *Diversity and Distributions*, **19(4)**, 363-376.

Carlsson-Kanyama, A., H. Carlsen, and K.H. Dreborg, 2013: Barriers in municipal climate change adaptation: results from case studies using backcasting. *Futures*, **49**, 9-21.

Cardona, O.D., M.K. van Aalst, J. Birkmann, M. Fordham, G. McGregor, R. Perez, R.S. Pulwarty, E.L.F. Schipper, and B.T. Sinh, 2012: Determinants of risk: exposure and vulnerability. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 65-108.

Carmin, J., N. Nadkarni, and C. Rhie, 2012: *Progress and Challenges in Urban Climate Adaptation Planning: Results of a Global Survey*. Massachusetts Institute of Technology (MIT), Department of Urban Studies and Planning, Cambridge, MA, USA, 30 pp.

Cash, D.W., W.N. Adger, F. Berkes, P. Garden, L. Lebel, P. Olsson, L. Pritchard, and O. Young, 2006: Scale and cross-scale dynamics: governance and information in a multilevel world. *Ecology and Society*, **11(2)**, 8, www.ecologyandsociety.org/vol11/iss2/art8/.

CBD, 2009: *Connecting Biodiversity and Climate Change Mitigation and Adaptation: Report of the Second Ad Hoc Technical Expert Group on Biodiversity and Climate*. CBD Technical Series No. 41, Secretariat of the Convention on Biological Diversity (CBD), Montreal, QC, Canada, 126 pp.

CCSP, 2009: *Thresholds of Climate Change in Ecosystems*. Synthesis and Assessment Product 4.2, Report by the U.S. Global Change Research Program and the Subcommittee on Global Change Research [Fagre, D.B., C.W. Charles, C.D. Allen, C. Birkeland, F.S. Chapin III, P.M. Groffman, G.R. Guntenspergen, A.K. Knapp, A.D. McGuire, P.J. Mulholland, D.P.C. Peters, D.D. Roby, and G. Sugihara (authors)]. U.S. Geological Survey (USGS), Reston, VA, USA, 156 pp.

CDP, 2012: *Insights into Climate Change Adaptation by UK Companies.* Commissioned by the Department for Environment, Food and Rural Affairs (DEFRA), Carbon Disclosure Project (CDP), London, UK, 55 pp.

Charmantier, A., R.H. McCleery, L.R. Cole, C. Perrins, L.E.B. Kruuk, and B.C. Sheldon, 2008: Adaptive phenotypic plasticity to climate change in a wild bird population. *Science*, **320**, 1024-1026.

Chapin III, F.S., S.R. Carpenter, G.P. Kofinas, C. Folke, N. Abel, W.C. Clark, P. Olsson, D.M. Stafford Smith, B. Walker, O.R. Young, F. Berkes, R. Biggs, J.M. Grove, R.L. Naylor, E. Pinkerton, W. Steffen, and F.J. Swanson, 2010: Ecosystem stewardship: sustainability strategies for a rapidly changing planet. *Trends in Ecology & Evolution*, **25(4)**, 241-249.

Chen, A. and W.C. Chang, 2012: Human health and thermal comfort of office workers in Singapore. *Building and Environment*, **58**, 172-178.

Chen, D., X. Ma, H. Mu, and P. Li, 2010: The inequality of natural resources consumption and its relationship with the social development level based on the ecological footprint and the HDI. *Journal of Environmental Assessment Policy and Management*, **12**, 69-86.

Chen, I.C., J.K. Hill, R. Ohlemüller, D.B. Roy, and C.D. Thomas, 2011: Rapid range shifts of species associated with high levels of climate warming. *Science*, **333(6045)**, 1024-1026.

Chhetri, N.B., W.E. Easterling, A. Terando, and L. Mearns, 2010: Modeling path dependence in agricultural adaptation to climate variability and change. *Annals of the Association of American Geographers*, **100(4)**, 894-907.

Chhetri, N., P. Chaudhary, P.R. Tiwari, and R.B. Yadaw, 2012: Institutional and technological innovation: Understanding agricultural adaptation to climate change in Nepal. *Applied Geography*, **33**, 142-150.

Chiew, F.H.S., W.J. Young, W. Cai, and J. Teng, 2011: Current drought and future hydroclimate projections in southeast Australia and implications for water resources management. *Stochastic Environmental Research and Risk Assessment*, **25(4)**, 601-612.

Chin, A., P.M. Kyne, T.I. Walker, and R.B. McAuley, 2010: An integrated risk assessment for climate change: analysing the vulnerability of sharks and rays on Australia's Great Barrier Reef. *Global Change Biology*, **16(7)**, 1936-1953.

Chowdhury, A.M.R., A.U. Bhuyia, A.Y. Choudhury, and R. Sen, 1993: The Bangladesh cyclone of 1991: why so many people died. *Disasters*, **17(4)**, 291-304.

Christensen, O.B., C.M. Goodess, I. Harris, and P. Watkiss, 2011: European and global climate change projections: discussion of climate change model outputs, scenarios and uncertainty in the EC RTD ClimateCost Project. In: *The Climate Cost Project, Final Report. Volume 1: Europe* [Watkiss, P. (ed.)]. Technical Policy Briefing Note 01, Stockholm Environment Institute (SEI), Stockholm, Sweden.

Clar, C., A. Prutsch, and R. Steurer, 2013: Barriers and guidelines for public policies on climate change adaptation: a missed opportunity of scientific knowledge-brokerage. *Natural Resources Forum*, **37(1)**, 1-18.

Clark, D, D. Lee, M. Freeman, and S. Clark, 2008: Polar bear conservation in Canada: defining the policy problems. *Arctic*, **61(4)**, 347-360.

Clark, J.S., D.M. Bell, M.H. Hersh, and L. Nichols, 2011: Climate change vulnerability of forest biodiversity: climate and resource tracking of demographic rates. *Global Change Biology*, **17**, 1834-1849.

Colwell, R.K., G. Brehm, C.L. Cardelús, A.C. Gilman, and J.T. Longino, 2008: Global warming, elevational range shifts, and lowland biotic attrition in the wet tropics. *Science*, **322(5899)**, 258-261.

Commonwealth of Australia, 2010: *Securing our Water Future.* Australian Government, Department of the Environment, Water, Heritage and the Arts, Canberra, ACT, Australia, 24 pp.

Connell, D. and R.Q. Grafton, 2011: Water reform in the Murray-Darling Basin. *Water Resources Research*, **47**, W00G03, doi:10.1029/2010WR009820.

Côté, I.M. and E.S. Darling, 2010: Rethinking ecosystem resilience in the face of climate change. *PLoS Biology,* **8(7)**, e1000438, doi:10.1371/journal.pbio.1000438.

Craig, R.K., 2010: "Stationarity is dead" – long live transformation: five principles for climate change adaptation law. *Harvard Environmental Law Review*, **34**, 9-73.

Crespo Cuaresma, J., J. Hlouskova, and M. Obersteiner, 2008: Natural disasters as creative destruction? Evidence from developing countries. *Economic Inquiry*, **46**, 214-226.

Crowley, P., 2011: Interpreting 'dangerous' in the United Nations framework convention on climate change and the human rights of Inuit. *Regional Environmental Change*, **11(1)**, 265-274.

Crutzen, P.J., 2002: Geology of mankind. *Nature*, **415(6867)**, 23.

Cutter, S.L. and C.T. Emrich, 2006: Moral hazard, social catastrophe: the changing face of vulnerability along the hurricane coasts. *The Annals of the American Academy of Political and Social Science*, **604(1)**, 102-112.

Cutter, S., B. Osman-Elasha, J. Campbell, S. Cheong, S. McCormick, R. Pulwarty, S. Supratid, and G. Ziervogel, 2012: Managing the risks from climate extremes at the local level. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 291-338.

Dale, V.H., R.A. Efroymson, and K.L. Kline, 2011: The land use–climate change–energy nexus. *Landscape Ecology*, **26(6)**, 755-773.

Das, S. and J.R. Vincent, 2009: Mangroves protected villages and reduced death toll during Indian super cyclone. *Proceedings of the National Academies of Sciences of the United States of America*, **106(18)**, 7357-7360.

Dasgupta, S., M. Huq, Z. Khan, M. Ahmed, N. Mukherjee, M. Khan, and K. Pandey, 2010: *Vulnerability of Bangladesh to Cyclones in a Changing Climate: Potential Damages and Adaptation Cost*. Policy Research Working Paper No. 5280, Environment and Energy Team, Development Research Group, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 54 pp.

de Bruin, K. and R.B. Dellink, 2011: How harmful are restrictions on adapting to climate change? *Global Environmental Change*, **21(1)**, 34-45.

de Bruin, K., R.B. Dellink, and S. Agrawala, 2009a: *Economic Aspects of Adaptation to Climate Change: Integrated Assessment Modelling of Adaptation Costs and Benefits.* OECD Publishing, Paris, France, 48 pp.

de Bruin, K., R.B. Dellink, A. Ruijs, L. Bolwidt, A. van Buuren, J. Graveland, R.S. de Groot, P.J. Kuikman, S. Reinhard, R.P. Roetter, V.C. Tassone, A. Verhagen, and E.C. van Ierland, 2009b: Adapting to climate change in The Netherlands: an inventory of climate adaptation options and ranking of alternatives. *Climatic Change*, **95(1-2)**, 23-45.

Delgado, J.A., P. M. Groffman, M.A. Nearing, T. Goddard, D. Reicosky, R. Lal, and P. Salon, 2011: Conservation practices to mitigate and adapt to climate change. *Journal of Soil and Water Conservation*, **66(4)**, 118A-129A.

Dellink, R., M. den Elzen, H. Aiking, E. Bergsma, F. Berkhout, T. Dekker, and J. Gupta, 2009: Sharing the burden of adaptation financing. *Global Environmental Change*, **19**, 411-421.

deMenocal, P.B., 2001: Cultural responses to climate change during the late Holocene. *Science*, **292(5517)**, 667-673.

Denton, F., 2010: Financing adaptation in least developed countries in West Africa: is finance the 'real deal'? *Climate Policy*, **10(6)**, 655-671.

Deressa, T.T., R.M. Hassan, C. Ringler, T. Alemu, and M. Yesuf, 2009: Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia. *Global Environmental Change*, **19(2)**, 248-255.

Deressa, T.T., R.M. Hassan, and C. Ringler, 2011: Perception of and adaptation to climate change by farmers in the Nile basin of Ethiopia. *Journal of Agricultural Science*, **149**, 23-31.

Dessai, S., M. Hulme, R. Lempert, and R.A. Pielke Jr., 2009: Do we need more precise and accurate predictions in order to adapt to a changing climate. *Eos*, **90(13)**, 111-112.

Devine-Wright, P., 2009: Rethinking nimbyism: the role of place attachment and place identity in explaining place-protective action. *Journal of Community and Applied Social Psychology*, **19,** 426-441.

Diamond, J.D., 2005: *Collapse: How Societies Choose to Fail or Succeed*. Penguin Books, New York, NY, USA, 575 pp.

Diaz, R. and R. Rosenberg, 2008: Spreading dead zones and consequences for marine ecosystems. *Science*, **321(5891)**, 926-929.

Baldassarre, G., A. Montanari, H. Lins, D. Koutsoyiannis, L. Brandimarte, and G. Blöschl, 2010: Flood fatalities in Africa: from diagnosis to mitigation. *Geophysical Research Letters*, **37(22)**, doi:10.1029/2010GL045467.

Dirnböck, T., F. Essl, and W. Rabitsch, 2011: Disproportional risk for habitat loss of high-altitude endemic species under climate change. *Global Change Biology*, **17(2)**, 990-996.

Dobes, L., 2008: Getting real about adapting to climate change: using 'real options' to address the uncertainties. *Agenda*, **15**, 55-72.

Dolcinar, S., A. Hurlimann, and B. Grun, 2011: What affects public acceptance of recycled and desalinated water? *Water Research*, **45(2)**, 933-943.

Donelson, J.M., P.L. Munday, M.I. McCormick, and C.R. Pitcher, 2011: Rapid transgenerational acclimation of a tropical reef fish to climate change. *Nature Climate Change*, **2(1)**, 30-32.

Doney, S.C., M. Ruckelshaus, J.E. Duffy, J.P. Barry, F. Chan, C.A. English, H.M. Galindo, J.M. Grebmeier, A.B. Hollowed, N. Knowlton, J. Polovina, N.N. Rabalais, W.J. Sydeman, and L.D. Talley, 2012: Climate change impacts on marine ecosystems. *Marine Science*, **4**, 11-37.

Donohew, Z. 2008: Property rights and western United States water markets. *The Australian Journal of Agricultural and Resource Economics*, **53**, 85-103.

Dovers, S., 2010: Normalizing adaptation. *Global Environmental Change*, **19**, 4-6.

Dovers, S. and R. Hezri, 2010: Institutions and policy processes: the means to the ends of adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, **1(2)**, 212-231.

Dow, K., F. Berkhout, and B.L. Preston, 2013a: Limits to adaptation: a risk approach. *Current Opinion in Environmental Sustainability*, **5(3-4)**, 384-391.

Dow, K., F. Berkhout, B.L. Preston, R.J.T. Klein, G. Midgley, and R. Shaw, 2013b: Limits to adaptation. *Nature Climate Change*, **3**, 305-307.

Dryden-Cripton, S., J. Smithers, R. de Loë, and R. Kreutzwiser, 2007: *An Evaluation of Options for Responding to Agricultural Droughts and Water Shortages in Canada.* Final Report, Prepared by the Guelph Water Management Group for Natural Resources Canada, Climate Change Impacts and Adaptation Program, Guelph Water Management Group, University of Guelph, Guelph, ON, Canada, 68 pp.

Drysdale, R., G. Zanchetta, J. Hellstrom, R. Maas, A. Fallick, M. Pickett, I. Cartwright, and L. Piccini, 2006: Late Holocene drought responsible for the collapse of Old World civilizations is recorded in an Italian cave flowstone. *Geology*, **34(2)**, 101-104.

Dugmore, A.J., C. Keller, T.H. McGovern, A.F. Casely, and K. Smiarowski, 2009: Norse Greenland settlement and limits to adaptation. In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, W.N., I. Lorenzoni, and K.L. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK, pp. 96-113.

Dukes, J.S., J. Pontius, D. Orwig, J.R. Garnas, V.L. Rodgers, N. Brazee, and M. Ayres, 2009: Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: what can we predict? *Canadian Journal of Forest Research*, **39(2)**, 231-248.

Dugmore, A.J., T.H. McGovern, O. Vesteinsson, J. Arneborg, R. Streeter, and C. Keller, 2012: Cultural adaptation, compounding vulnerabilities and conjunctures in Norse Greenland. *Proceedings of the National Academy of Sciences of the United States of America*, **109(10)**, 3658-3663.

Dunlop, M. and P. Brown, 2008: *Implications of Climate Change for Australia's National Reserve System: A Preliminary Assessment.* A Report to the Australian Government, Department of Climate Change and the Department of the Environment, Water, Heritage and the Arts, Department of Climate Change, Canberra, ACT, Australia, 188 pp.

Dunning, N.P., T.P. Beach, and S. Luzzadder-Beach, 2012: Kax and kol: collapse and resilience in lowland Maya civilization. *Proceedings of the National Academy of Sciences of the United States of America*, **109(10)**, 3652-3657.

Duru, M., B. Felten, J.P. Theau, and G. Martin, 2012: A modelling and participatory approach for enhancing learning about adaptation of grassland-based livestock systems to climate change. *Regional Environmental Change*, **12(4)**, 739-750.

Eakin, H., A. Winkels, and J. Sendzimir, 2009: Nested vulnerability: exploring cross-scale linkages and vulnerability teleconnections in Mexican and Vietnamese coffee systems. *Environmental Science & Policy*, **12(4)**, 398-412.

EBI, 2013: *Emerging Business Opportunities in the Climate Change Adaptation Industry*. EBI Report 4800, Climate Change Business Journal, A Climate Change Industry Business Segment Review by Environmental Business International (EBI), Inc., San Diego, CA, USA, 6 pp.

Ebi, K. and J. Semenza, 2008: Community-based adaptation to the health impacts of climate change. *American Journal of Preventive Medicine*, **35(5)**, 501-507.

Ebi, K.L., J. Balbus, P.L. Kinney, E. Lipp, D. Mills, M.S. O'Neill, and M.L. Wilson, 2009: US funding is insufficient to address the human health impacts of and public health responses to climate variability and change. *Environmental Health Perspectives*, **117(6)**, 857-862

Ebi, K.L., J. Padgham, M. Doumbia, J. Smith, T. Butt, and B. McCarl, 2011: Smallholders adaptation to climate change in Mali. *Climatic Change*, **108(3)**, 423-436.

Ebi, K.L., S. Hallegatte, T. Kram, N.W. Arnell, T.R. Carter, J. Edmonds, E. Kriegler, R. Mathur, B. O'Neill, K. Riahi, H. Winkler, D.P. Van Vuuren, and T. Zwickel, 2013: A new scenario framework for climate change research: background, process, and future directions. *Climatic Change*, doi:10.1007/s10584-013-0912-3.

Edwards, B., M. Gray, and B. Hunter, 2009: A sunburnt country: the economic and financial impact of drought on rural and regional families in Australia in an era of climate change. *Australian Journal of Labour Economics*, **12(1)**, 109-131.

Edvardsson-Bjornberg, K. and S.O. Hansson, 2011: Five areas of value judgement in local adaptation to climate change. *Local Government Studies*, **37(6)**, 671-687.

Eisenack, K. and R. Stecker; 2012: A framework for analyzing climate change adaptations as actions. *Mitigation and Adaptation Strategies for Global Change*, **17**, 243-260.

Eisenack, K., R. Stecker, D. Reckien, and E. Hoffmann, 2012: Adaptation to climate change in the transport sector: a review of actions and actors. *Mitigation and Adaptation Strategies for Global Change*, **17(5)**, 451-469.

Endfield, G.H., 2012: The resilience and adaptive capacity of social-environmental systems in colonial Mexico. *Proceedings of the National Academy of Sciences of the United States of America*, **109(10)**, 3676-3681.

Engle, N.L. and M.C. Lemos, 2010: Unpacking governance: building adaptive capacity to climate change of river basins in Brazil. *Global Environmental Change*, **20(1)**, 4-13.

Engler, R., C.F. Randin, P. Vittoz, T. Czáka, M. Beniston, N.E. Zimmermann, and A. Guisan, 2009: Predicting future distributions of mountain plants under climate change: does dispersal capacity matter? *Ecography*, **32(1)**, 34-45.

Eriksen, S., P. Aldunce, C.S. Bahinipati, R.D.A. Martins, J.I. Molefe, C. Nhemachena, K. O'Brien, F. Olorunfemi, J. Park, L. Sygna, and K. Ulsrud, 2011: When not every response to climate change is a good one: identifying principles for sustainable adaptation. *Climate and Development*, **3(1)**, 7-20.

EC, 2013: *Guidelines on Developing Adaptation Strategies*. Brussels, 16.4.2013, SWD(2013), 134 final, Commission Staff Working Document accompanying, "Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions," an EU Strategy on adaptation to climate change, European Commission (EC), Brussels, Belgium, 54 pp.

EPA, 2009: *Synthesis of Adaptation Options for Coastal Areas*. EPA 430-F-08-024, Climate Ready Estuaries Program, U.S. Environmental Protection Agency (EPA), Washington, DC, USA, 25 pp.

Fankhauser, S. and R. Soare, 2013: An economic approach to adaptation: illustrations from Europe. *Climatic Change*, **118**, 367-379.

FAO, 2011: *The Food Security in the World. How Does Food Price Volatility Affect Domestic Economies and Food Security?* Food and Agriculture Organisation of the United Nations (FAO), Rome, Italy, 52 pp.

FAO, 2013: *Climate-Smart Agriculture Sourcebook*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 557 pp.

Fatti, C.E. and Z. Patel, 2013: Perceptions and responses to urban flood risk: implications for climate governance in the South. *Applied Geography*, **36**, 13-22.

Faysse, N., J.D. Rinaudo, S. Bento, A. Richard-Ferroudji, M. Errahj, M. Varanda, A. Imache, M. Dionnet, D. Rollin, P. Garin, M. Kuper, L. Maton, and M. Montginoul, 2012: Participatory analysis for adaptation to climate change in Mediterranean agricultural systems: possible choices in process design. *Regional Environmental Change*, doi:10.1007/s10113-012-0362-x.

Fedoroff, N.V., D.S. Battisti, R.N. Beachy, P.J.M. Cooper, D.A. Fischhoff, C.N. Hodges, V.C. Knauf, D. Lobell, B.J. Mazur, D. Molden, M.P. Reynolds, P.C. Ronald, M.W. Rosegrant, P.A. Sanchez, A. Vonshak, and J.K. Zhu, 2010: Radically rethinking agriculture for the 21st century. *Science*, **327**, 833-834.

Feeley, K.J. and M.R. Silman, 2010: Land-use and climate change effects on population size and extinction risk of Andean plants. *Global Change Biology*, **16(12)**, 3215-3222.

Feeley, K.J., E.M. Rehm, and B. Machovina, 2012: Perspective: the responses of tropical forest species to global climate change: acclimate, adapt, migrate, or go extinct? *Frontiers of Biogeography*, **4(2)**, 69-84.

Felgenhauer, T. and K.C. de Bruin, 2009: The optimal paths of climate change mitigation and adaptation under certainty and uncertainty. *International Journal of Global Warming*, **1(1-3)**, 66-88.

Feng, S., A.B. Krueger, and M. Oppenheimer, 2010: Linkages among climate change, crop yields and Mexico-US cross-border migration. *Proceedings of the National Academy of Sciences of the United States of America*, **107(32)**, 14257-14262.

Field, C.B., L.D. Mortsch, M. Brklacich, D.L. Forbes, P. Kovacs, J.A. Patz, S.W. Running, and M.J. Scott, 2007: North America. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 617-652.

Fisher, B.S., N. Nakicenovic, K. Alfsen, J. Corfee Morlot, F. de la Chesnaye, J.-C. Hourcade, K. Jiang, M. Kainuma, E. La Rovere, A. Matysek, A. Rana, K. Riahi, R. Richels, S. Rose, D. van Vuuren, and R. Warren, 2007: Issues related to mitigation in the long-term context. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 169-250.

Fiksel, J., 2006: Sustainability and resilience: towards a systems approach. *Sustainability Science Practice and Policy*, **2(2)**, 14-21.

Flåm, K.H. and J.B. Skjærseth, 2009: Does adequate financing exist for adaptation in developing countries? *Climate Policy*, **9(1)**, 109-114.

Fleischer, A., R. Mendelsohn, and A. Dinar, 2011: Bundling agricultural technologies to adapt to climate change. *Technological Forecasting and Social Change*, **78(6)**, 982-990.

Foale, S.J., 2008: Conserving Melanesia's coral reef heritage in the face of climate change. *Historic Environment* **18**, 30-36.

Ford, J.D., 2009: Dangerous climate change and the importance of adaptation for the Arctic's Inuit population. *Environmental Research Letters*, **4(2)**, 024006, doi:10.1088/1748-9326/4/2/024006.

Ford, J.D., J. MacDonald, B. Smit, and J. Wandel, 2006: Vulnerability to climate change in Igloolik, Nunavut: what we can learn from the past and present. *Polar Record*, **42(2)**, 1-12.

Ford, J.D., T. Pearce, F. Duerden, C. Furgal, and B. Smit, 2010: Climate change policy responses for Canada's Inuit population: the importance of and opportunities for adaptation. *Global Environmental Change*, **20**, 177-191.

Ford, J.D., L. Berrang-Ford, and J. Paterson, 2011: A systematic review of observed climate change adaptation in developed nations. A letter. *Climatic Change*, **160**, 237-336.

Foresight, 2011: *Migration and Global Environmental Change: Future Challenges and Opportunities*. Final Project Report, The UK Government Office for Science, London, UK, 237 pp.

Fosu-Mensah, B.Y., P.L.G. Vlek, and D.S. MacCarthy, 2012: Farmers' perception and adaptation to climate change: a case study of Sekyedumase district in Ghana. *Environment, Development and Sustainability*, **14**, 495-505.

Frank, S., C. Fürst, L. Koschke, and F. Makeschin, 2011: A contribution toward the transfer of the ecosystem service concept to landscape planning using landscape metrics. *Ecological Indicators*, **21**, 30-38.

Fresque-Baxter, J.A. and D. Armitage, 2012: Place identity and climate change adaptation: a synthesis and framework for understanding. *Wiley Interdisciplinary Reviews: Climate Change*, **3**, 251-266.

Fuller, S. and H. Bulkeley, 2012: Changing countries, changing climates: achieving thermal comfort through adaptation in everyday activities. *Area*, **45(1)**, 63-69.

Fünfgeld, H. and D. McEvoy, 2011: *Framing Climate Change Adaptation in Policy and Practice*. Working Paper 1, Victorian Center for Climate Change Adaptation Research, Melbourne, VIC, Australia, 65 pp.

Fung, F., A. Lopez, and M. New, 2011: Water availability in +2°C and +4°C worlds. *Philosophical Transactions of the Royal Society A*, **369(1934)**, 99-116.

Füssel, H.M., 2006: Reducing the risk of a collapse of the Atlantic thermohaline circulation: a comment. *The Integrated Assessment Journal*, **6(3)**, 51-58.

Füssel, H.M., 2008: Assessing adaptation to the health risks of climate change: what guidance can existing frameworks provide? *International Journal of Environmental Health Research*, **18(1)**, 37-63.

Füssel, H., 2009: Ranking of national-level adaptation options. An editorial comment. *Climatic Change*, **95(1-2)**, 47-51.

Füssel, H., 2010: How inequitable is the global distribution of responsibility, capability, and vulnerability to climate change: a comprehensive indicator-based assessment. *Global Environmental Change*, **20(4)**, 597-611.

Füssel, H. and R.J.T. Klein, 2006: Climate change vulnerability assessments: an evolution of conceptual thinking. *Climatic Change*, **75(3)**, 301-329.

Gale, M.K., S.G. Hinch, E.J. Eliason, S.J. Cooke, and D.A, Patterson, 2011: Physiological impairment of adult sockeye salmon in fresh water after simulated capture-and-release across a range of temperatures. *Fisheries Research*, **112(1)**, 85-95.

Gall, M., K.A. Borden, C.T. Emrich, and S.L. Cutter, 2011: The unsustainable trend of natural hazard losses in the United States. *Sustainability*, **3**, 2157-2181.

Gardiner, S.M., 2006: A perfect moral storm: climate change, intergenerational ethics and the problem of moral corruption. *Environmental Values*, **15**, 397-413.

Gardiner, S.M., 2010: A perfect moral storm. Climate change, intergenerational ethics, and the problem of corruption. In: *Climate Ethics: Essential Readings* [Gardiner, S.M., S. Caney, D. Jamieson, and H. Shue (eds.)]. Oxford University Press, Oxford, UK, pp. 87-100.

Gardner, J., R. Parsons, and G. Paxton, 2010: *Adaptation Benchmarking Survey: Initial Report.* CSIRO Climate Adaptation Flagship Working Paper No. 4, The Commonwealth Scientific and Industrial Research Organisation (CSIRO), Clayton, South VIC, Australia, 58 pp.

Garfi, M., L. Ferrer-Martí, A. Bonoli, and S. Tondelli, 2011: Multi-criteria analysis for improving strategic environmental assessment of water programmes. A case study in semi-arid region of Brazil. *Journal of Environmental Management*, **92(3)**, 665-675.

Garnaut, R., 2011: *The Garnaut Review 2011: Australia in the Global Response to Climate Change*. Cambridge University Press, New York, NY, USA, 244 pp.

Garschagen, M., 2013: Resilience and organisational institutionalism from a cross-cultural perspective: an exploration based on urban climate change adaptation in Vietnam. *Natural Hazards*, **67(1)**, 25-46.

Gedan, K.B., M.L. Kirwan, E. Wolanski, E.B. Barbier, and B.R. Silliman, 2011: The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. *Climatic Change*, **106**, 7-29.

Gemenne, F., 2011: Climate-induced population displacements in a 4°C+ world. *Philosophical Transactions of the Royal Society A*, **369(1934)**, 182-195.

Gienapp, P., C. Teplitsky, J. Alho, J. Mills, and J. Merilä, 2008: Climate change and evolution: disentangling environmental and genetic responses. *Molecular Ecology*, **1(167)**, 167-178.

Gilman, E.L., J. Ellison, N.C. Duke, and C. Field, 2008: Threats to mangroves from climate change and adaptation options: a review. *Aquatic Botany*, **89(2)**, 237-250.

GIZ, 2011a: *Making Adaptation Count: Concepts and Options for Monitoring and Evaluation of Climate Change Adaptation*. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH on behalf of Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (BMZ), GIZ, Eschborn, Germany, 92 pp.

GIZ, 2011b: *Adaptation to Climate Change: New Findings, Methods and Solutions*. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH on behalf of Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (BMZ), GIZ, Eschborn, Germany, 35 pp.

Gordon, J.S., J.B. Gruver, C.G. Flint, and A.E. Luloff, 2013: Perceptions of wildfire and landscape change in the Kenai Peninsula, Alaska. *Environmental Management*, **52(4)**, 807-820.

Gorman-Murray, A., 2010: An Australian feeling for snow: towards understanding cultural and emotional dimensions of climate change. *Cultural Studies Review*, **16**, 60-81.

Goulden, M., D. Conway, and A. Persechino, 2009: Adaptation to climate change in international river basins in Africa: a review. *Hydrological Sciences Journal*, **54(5)**, 805-828.

Grasso, M. 2010. An ethical approach to climate adaptation finance. *Global Environmental Change*, **20**, 74-81.

Gregory P.J., J.S.I. Ingram, and M. Brklacich, 2005: Climate change and food security. *Philosophical Transactions of the Royal Society B*, **360**, 2139-2148.

Grothmann, T., 2011: Governance recommendations for adaptation in European urban regions: results from five case studies and a European expert survey. In: *Resilient Cities: Cities and Adaptation to Climate Change* [Otto-Zimmermann, K. (ed.)]. Springer, Dordrecht, Netherlands, pp. 167-176.

Grothmann, T. and A. Patt, 2005: Adaptive capacity and human cognition: the process of individual adaptation to climate change. *Global Environmental Change*, **15**, 199-213.

Gupta, J., C. Termeer, J. Klostermann, S. Meijerink, M. van den Brink, P. Jong, S. Nooteboom, and E. Bergsma, 2010: The adaptive capacity wheel: a method to assess the inherent characteristics of institutions to enable the adaptive capacity of society. *Environmental Science & Policy*, **13(6)**, 459-471.

Haasnoot, M., J.H. Kwakkel, W.E.Walker, and J. ter Maat, 2013: Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, **23(2)**, 485-498.

Habib, A., M. Shahidullah, and D. Ahmed, 2012: The Bangladesh cyclone preparedness program. A vital component of the nation's multi-hazard early warning system. In: *Institutional Partnerships in Multi-Hazard Early Warning Systems.* Springer, Berlin Heidelberg, Germany, pp. 29-62.

Haddad, B.M., 2005: Ranking the adaptive capacity of nations to climate change when socio-political goals are explicit. *Global Environmental Change*, **15**, 165-176.

Hall, J.W., S. Brown, R.J. Nicholls, N. Pidgeon, and R.T. Watson, 2012: Proportionate adaptation. *Nature Climate Change*, **2**, 833-834.

Hallegatte, S., 2009: Strategies to adapt to an uncertain climate change. *Global Environmental Change*, **19(2)**, 240-247.

Hamilton, L.C., 2011: Education, politics and opinions about climate change evidence for interaction effects. *Climatic Change*, **104(2)**, 231-242.

Hamin, E.M. and N. Gurran, 2009: Urban form and climate change: balancing adaptation and mitigation in the US and Australia. *Habitat International*, **33(3)**, 238-245.

Hanemann, W.M., 2008: *What is the Economic Cost of Climate Change?* CUDARE Working Paper Series No. 1071, University of California at Berkeley, Department of Agricultural and Resource Economics and Policy, Berkeley, CA, USA, 15 pp.

Hanjra, M.A. and M.E. Qureshi, 2010: Global water crisis and future food security in an era of climate change. *Food Policy*, **25(5)**, 365-377.

Hare, W.L., W. Cramer, M. Schaeffer, A. Battaglini, and C.C. Jaeger, 2011: Climate hotspots: key vulnerable regions, climate change and limits to warming. *Regional Environmental Change*, **11(Suppl. 1)**, S1-S13.

Harley, C.D., A. Randall Hughes, K.M. Hultgren, B.G. Miner, C.J. Sorte, C.S. Thornber, and S.L. Williams, 2006: The impacts of climate change in coastal marine systems. *Ecology Letters*, **9(2)**, 228-241.

Harris, S.E., 2012: Cyprus as a degraded landscape or resilient environment in the wake of colonial intrusion. *Proceedings of the National Academy of Sciences of the United States of America*, **109(10)**, 3670-3675.

Hartley, T.W., 2006: Public perception and participation in water reuse. *Desalination*, **187(1-3)**, 115-126.

Hartzell-Nichols, L., 2011: Responsibility for meeting the costs of adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, **2(5)**, 687-700.

Hassan, R. and C. Nhemachena, 2008: Determinants of African farmers' strategies for adapting to climate change: multinomial choice analysis, *African Journal of Agricultural and Resource Economics*, **2(1)**, 83-104.

Hayward, B. 2008: 'Nowhere far from sea': political challenges of coastal adaptation to climate change in New Zealand. *Political Science*, **1**, 47-59.

Heeres, N., T. Tillema, and J. Arts, 2012: Integration in Dutch planning of motorways: from "line" towards "area-oriented" approaches. *Transport Policy*, **24**, 148-158.

Hellmann, J.J., J.E. Byers, B.G. Bierwagen, and J.S. Dukes, 2008: Five potential consequences of climate change for invasive species. *Conservation Biology*, **22(3)**, 534-543.

Hellmann, J.J., K.M. Prior, and S.L. Pelini, 2012: The influence of species interactions on geographic range change under climate change. *Annals of the New York Academy of Sciences*, **1249(1)**, 18-28.

Heltberg, R., P.B. Siegel, and S.L. Jorgensen, 2009: Addressing human vulnerability to climate change: toward a 'no-regrets' approach. *Global Environmental Change*, **19(1)**, 89-99.

Hennessy, K., B. Fitzharris, B.C. Bates, N. Harvey, S.M. Howden, L. Hughes, J. Salinger, and R. Warrick, 2007: Australia and New Zealand. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 507-540.

Herrfahrdt-Pähle, E., 2013: Integrated and adaptive governance of water resources: the case of South Africa. *Regional Environmental Change*, **13(3)**, 551-561.

Hertel, T.W. and S. Rosch, 2010: Climate change agriculture and poverty. *Applied Economic Perspectives and Policy*, **32(3)**, 355-385.

Hertzler, G., 2007: Adapting to climate change and managing climate risks by using real options. *Crop and Pasture Science*, **58(10)**, 985-992.

Herweijer, C., N. Ranger, and R.E.T. Ward, 2009: Adaptation to climate change: threats and opportunities for the insurance industry. *The Geneva Papers*, **34**, 360-380.

Hess, J., J.N. Malilay, and A.J. Parkinson, 2008: Climate change: the importance of place. *American Journal of Preventive Medicine*, **35(5)**, 468-478.

Heyd, T. and N. Brooks, 2009: Exploring cultural dimensions of adaptation to climate change. In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, W.N., I. Lorenzoni, and K.L. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK, pp. 269-82.

Hill, J.K., H.M. Griffiths, and C.D. Thomas, 2011: Climate change and evolutionary adaptations at species' range margins. *Annual Review of Entomology*, **56**, 143-159.

Hillie, T. and M. Hlophe, 2007: Nanotechnology and the challenge of clean water. *Nature Nanotechnology*, **2**, 663-664.

Hinkel, J., 2011: Indicators of vulnerability and adaptive capacity: towards a clarification of the science. *Global Environmental Change*, **21**, 198-208.

Hisali, E., P. Birungi, and F. Buyinza, 2011: Adaptation to climate change in Uganda: evidence from micro level data. *Global Environmental Change*, **21(4)**, 1245-1261.

Ho, M., D. Shaw, S. Lin, and Y. Chiu, 2008: How do disaster characteristics influence risk perceptions? *Risk Analysis*, **28(3)**, 635-643.

Hodgson, J.A., C.D Thomas, B.A. Wintle, and A. Moilanen, 2009: Assessing wave energy effects on biodiversity: the Wave Hub experience. *Philosophical Transactions of the Royal Society A*, **370(1959)**, 502-529.

Hoegh-Guldberg, O., 2008: Climate change and coral reefs: Trojan horse or false prophecy? *Coral Reefs*, **28**, 569-575.

Hoegh-Guldberg, O., 2011: Coral reef ecosystems and anthropogenic climate change. *Regional Environmental Change*, **11(1)**, 215-227.

Hof, A.F., K.C. de Bruin, R.B. Dellink, M.G.J. den Elzen, and D.P. van Vuuren, 2009: The effect of different mitigation strategies on international financing of adaptation. *Environmental Science & Policy*, **12(7)**, 832-843.

Hoffmann, A.A. and C.M. Sgrò, 2011: Climate change and evolutionary adaptation. *Nature*, **470**, 479-485.

Hope, C., 2011: *The PAGE09 Integrated Assessment Model: A Technical Description*. Working Paper Series 4/2011, University of Cambridge, Judge Business School, Cambridge, UK, 44 pp.

Howden, S.M., J.F. Soussana, F.N. Tubiello, N. Chhetri, M. Dunlop, and H. Meinke, 2007: Adapting agriculture to climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **104(50)**, 19691-19696.

Huang, C., P. Vaneckova, X. Wang, G. FitzGerald, Y. Guo, and S. Tong, 2011: Constraints and barriers to public health adaptation to climate change: a review of the literature. *American Journal of Preventive Medicine*, **40(2)**, 183-190.

Hulme, M., W.N. Adger, S. Dessai, M. Goulden, I. Lorenzoni, D. Nelson, L.O. Naess, J. Wolf, and A. Wreford, 2007: *Limits and Barriers to Adaptation: Four Propositions.* Tyndall Briefing Note No. 20, Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, UK, 7 pp.

Hulme, M., S. Dessai, I. Lorenzoni, and D.R. Nelson, 2009: Unstable climates: exploring the statistical and social constructions of 'normal' climate. *Geoforum*, **40(2)**, 197-206.

Hunt, T.L., 2007: Rethinking Easter Island's ecological catastrophe. *Journal of Archaeological Science*, **34(3)**, 485-502.

Huntington, H.P., E. Goodstein, and E. Euskirchen, 2012: Towards a tipping point in responding to change: rising costs, fewer options for Arctic and global societies. *Ambio*, **41(1)**, 66-74.

Huntjens, P., C. Pahl-Wostl, and J. Grin, 2010: Climate change adaptation in European river basins. *Regional Environmental Change*, **10**, 263-284.

Huntjens, P., L. Lebel, C. Pahl-Wostl, J. Camkin, R, Schulze, and N. Kranz, 2012: Institutional design propositions for the governance of adaptation to climate change in the water sector. *Global Environmental Change*, **22(1)**, 67-81.

Iglesias, A., L. Garrote, F. Flores, and M. Moneo, 2007: Challenges to manage the risk of water security and climate change in the Mediterranean. *Water Resources Management*, **21**, 775-788.

Iglesias, A., R. Mougou, M. Moneo, and S. Quiroga, 2011: Towards adaptation of agriculture to climate change in the Mediterranean. *Regional Environmental Change*, **11(Suppl. 1)**, 159-166.

Indraganti, M., 2010: Behavioural adaptation and the use of environmental controls in summer for thermal comfort in apartments in India. *Energy and Buildings*, **42(7)**, 1019-1025.

IPCC, 2007a: Summary for policymakers. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 7-22.

IPCC, 2007b: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M., O. Canziani, J. Palutikof, and P. van der Linden (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 976 pp.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp.

Islam, M., S. Sallu, K. Hubacek, and J. Paavola, 2014: Limits and barriers to adaptation to climate variability and change in Bangladeshi coastal fishing communities. *Marine Policy*, **43**, 208-216

Iwasaki, S., B.H.N. Razafindrabe, and R. Shaw, 2009: Fishery livelihoods and adaptation to climate change: a case study of Chilika Lagoon, India. *Mitigation and Adaptation Strategies for Global Change*, **14(4)**, 339-355.

Jäger, J. and P. Moll, 2011: Adaptation to climate change: tools and methods. *Regional Environmental Change*, **11(2)**, 213-215.

Jackson, A.C. and J. McIlvenny, 2011: Coastal squeeze on rocky shores in northern Scotland and some possible ecological impacts. *Journal of Marine Experimental Biology and Ecology*, **400**, 314-321.

Jacob, C., T. McDaniels, and S. Hinch, 2010: Indigenous culture and adaptation to climate change: sockeye salmon and the St'át'imc people. *Mitigation and Adaptation Strategies for Global Change*, **15**, 859-876.

Jantarasami, L.C., J.J. Lawler, and C.W. Thomas, 2010: Institutional barriers to climate change adaptation in U.S. national parks and forests. *Ecology and Society*, **15(4)**, 33, www.ecologyandsociety.org/vol15/iss4/art33/.

Jeffers, J.M., 2013: Double exposures and decision making: adaptation policy and planning in Ireland's coastal cities during a boom–bust cycle. *Environment and Planning A*, **45(6)**, 1436-1454.

Jenkins, K.M., R.T. Kingsford, B.J. Wolfenden, S. Whitten, H. Parris, C. Sives, and R. Rolls, 2011: *Limits to Climate Change Adaptation in Floodplain Wetlands: The Macquarie Marshes.* Final Report to the National Climate Change Adaptation Research Facility (NCCARF), Griffith University, Gold Coast Campus, Southport, Australia, 159 pp.

Jensen, L.F., M.M. Hansen, C. Pertoldi, G. Holdensgaard, K.L.D. Mensberg, and V. Loeschcke, 2008: Local adaptation in brown trout early life-history traits: implications for climate change adaptability. *Proceedings of the Royal Society B*, **275(1653)**, 2859-2868.

Jeuland, M. and D. Whittington, 2013: *Water Resources Planning under Climate Change: A "Real Options" Application to Investment Planning in the Blue Nile*. Environment for Development Discussion Paper Series, EfD DP 13-05, The Environment for Development (EfD) Initiative, Resources for the Future, Washington, DC, USA, 54 pp.

Johannessen, O.M. and M.W. Miles, 2011: Critical vulnerabilities of marine and sea ice-based ecosystems in the high Arctic. *Regional Environmental Change*, **11(Suppl. 1)**, S239-S248.

Jolibert, C., M. Max-Neef, F. Rauschmayer, and J. Paavola, 2011: Should we care about the needs of non-humans? Needs assessment: a tool for environmental conflict resolution and sustainable organization of living beings. *Environmental Policy and Governance*, **21**, 259-269.

Jones, L. and E. Boyd, 2011: Exploring social barriers to adaptation: insights from Western Nepal. *Global Environmental Change*, **21(4)**, 1262-1274.

Jones, R.N., 2001: An environmental risk assessment/management framework for climate change impact assessments. *Natural Hazards*, **23**, 197-230.

Jones, R.N., 2010: Water resources. In: *Adapting Agriculture to Climate Change* [Stokes, C. and M. Howden (eds.)]. CSIRO Publishing, Collingwood, Australia, pp. 187-204.

Jones, R.N. and A.B. Pittock, 2002: Climate change and water resources in an arid continent: managing uncertainty and risk in Australia. In: *Climatic Change: Implications for the Hydrological Cycle and for Water Management* [Beniston, M. (ed.)]. Kluwer Academic Publishers, Dordrecht, Netherlands and Boston, MA, USA, pp. 465-501.

Jones, R.N. and B.L. Preston, 2011: Adaptation and risk management. *Wiley Interdisciplinary Reviews: Climate Change*, **2**, 296-308.

Juhola, S. and L. Westerhoff, 2011: Challenges of adaptation to climate change across multiple scales: a case study of network governance in two European countries. *Environmental Science & Policy*, **14(3)**, 239-247.

Juhola, S., E.C.H. Keskitalo, and L. Westerhoff, 2011: Understanding the framings of climate change adaptation across multiple scales of governance in Europe. *Environmental Politics*, **20(4)**, 445-463.

Kahan, D.M., 2010: Fixing the communications failure. *Nature*, **463**, 296-297.

Kahan, D.M., E. Peters, M. Wittlin, P. Slovic, L.L. Ouellette, D. Braman, and G. Mandel, 2012: The polarizing impact of science literacy and numeracy on perceived climate change risks. *Nature Climate Change*, **2(10)**, 732-735.

Kalirajan, K., K. Singh, S. Thangavelu, A. Venkatachalam, and K. Perera, 2011: *Climate Change and Poverty Reduction: Where Does Official Development Assistance Money Go*? ADBI Working Paper Series, No. 318, Asian Development Bank Institute (ADBI), Tokyo, Japan, 43 pp.

Kapos, V. and L. Miles, 2008: Reducing greenhouse gas emissions from deforestation and forest degradation: global land-use implications. *Science*, **320(5882)**, 1454-1455.

Karim, M.F. and N. Mimura, 2008: Impacts of climate change and sea-level rise on cyclonic storm surge floods in Bangladesh. *Global Environmental Change*, **18(3)**, 490-500.

Kasperson, R.E. and M. Berberian (eds.), 2011: *Integrating Science and Policy: Vulnerability and Resilience in Global Environmental Change.* Earthscan, London, UK, 416 pp.

Kates, R., W. Travis, and T. Wilbanks, 2012: Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences of the Unites States of America*, **109(19)**, 7156-7161.

Kato, E., C. Ringler, M. Yesuf, and E. Bryan, 2011: Soil and water conservation technologies: a buffer against production risk in the face of climate change? Insights from the Nile basin in Ethiopia. *Agricultural Economics*, **42(5)**, 593-604.

Kellstedt, P.M., S. Zahran, and A. Vedlitz, 2008: Personal efficacy, the information environment, and attitudes toward global warming and climate change in the United States. *Risk Analysis*, **28**, 113-126.

Kenny, J.F., N.L. Barber, S.S. Hutson, K.S. Linsey, J.K. Lovelace, and M.A. Maupin, 2009: *Estimated Use of Water in the United States in 2005.* USGS Circular 1344, U.S. Department of the Interior, U.S. Geological Survey (USGS), Washington, DC, USA, 52 pp.

Keryn, B., M.L. Kirwan, E. Wolanski, E.B. Barbier, and B.R. Silliman, 2011: The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. *Climatic Change*, **106**, 7-29.

Keskitalo, E.C.H. (ed.), 2010: *The Development of Adaptation Policy and Practice in Europe: Multi-Level Governance of Climate Change.* Springer, Dordrecht, Netherlands, 376 pp.

Kiem, A.S. and E.K. Austin, 2013: Drought and the future of rural communities: opportunities and challenges for climate change adaptation in regional Victoria, Australia. *Global Environmental Change*, **23(5)**, 1307-1316.

Kiem, A.S., D.C. Verdon-Kidd, S.L. Boulter, and J.P. Palutikof, 2010: *Learning from Experience: Historical Case Studies and Climate Change Adaptation*. Report for the National Climate Change Adaptation Research Facility (NCCARF), Griffith University, Gold Coast Campus, Southport, Australia, 33 pp.

Klein, R.J.T., 2009: Identifying countries that are particularly vulnerable to the effects of climate change: an academic or political challenge? *Carbon Climate Law Review*, **3**, 284-291.

Klein, R.J.T., 2010: Linking adaptation and development finance: a policy dilemma not addressed in Copenhagen. *Climate and Development*, **2(3)**, 203-206.

Klein, R.J.T. and S. Juhola, 2013: *A Framework for Nordic Actor-Oriented Climate Adaptation Research.* NORD-STAR Working Paper 2013-01, Nordic Centre of Excellence for Strategic Adaptation Research (NORD-STAR), Aarhus University, Business and Social Sciences, Herning, Denmark, 20 pp.

Klein, R.J.T. and A. Möhner, 2009: Governance limits to effective global financial support for adaptation. In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, W.N., I. Lorenzoni, and K.L. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK, pp. 465-475.

Klein, R.J.T., S. Huq, F. Denton, T.E. Downing, R.G. Richels, J.B. Robinson, and F.L. Toth, 2007: Inter-relationships between adaptation and mitigation. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 745-777.

Klinke, A. and O. Renn, 2002: A new approach to risk evaluation and management: risk-based, precaution-based, and discourse-based strategies. *Risk Analysis*, **22**, 1071-1094.

Klinsky, S., H. Dowlatabadi, and T. McDaniels, 2012: Comparing public rationales for justice trade-offs in mitigation and adaptation climate policy dilemmas. *Global Environmental Change*, **22**, 862-876.

Knox, J.H., 2009: Linking human rights and climate change at the United Nations. *Harvard Environmental Law Review*, **33**, 477-498.

Koh, J., 2011: Local vulnerability assessment of climate change and its implications: the case of Gyeonggi-Do, Korea. In: *Resilient Cities: Cities and Adaptation to Climate Change –Proceedings of the Global Forum 2010, Vol. 1, Local Sustainability* [Otto-Zimmermann, K. (ed.)]. Springer Science, Dordrecht, Netherlands, pp. 411-427.

Koivurova, T., 2007: International legal avenues to address the plight of victims of climate change: problems and prospects. *Journal of Environmental Law and Litigation*, **22**, 267-299.

Kremer, A., O. Ronce, J.J. Robledo-Arnuncio, F. Guillaume, G. Bohrer, R. Nathan, and S. Schueler, 2012: Long-distance gene flow and adaptation of forest trees to rapid climate change. *Ecology Letters*, **15(4)**, 378-392.

Kriegler, E., J.W. Hall, H. Held, R. Dawson, and H.J. Schellnhuber, 2009: Imprecise probability assessment of tipping points in the climate system. *Proceedings of the National Academy of Sciences of the United States of America*, **106(13)**, 5041-5046.

Kriegler, E., B.C. O'Neill, S. Hallegatte, T. Kram, R.J. Lempert, R.H. Moss, and T. Wilbanks, 2012: The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathways. *Global Environmental Change*, **22(4)**, 807-822.

Krosby, M., J. Tewksbury, N.M. Haddad, and J. Hoekstra, 2010: Ecological connectivity for a changing climate. *Conservation Biology*, **24(6)**, 1686-1689.

Krysanova, V., C. Dickens, J. Timmerman, C. Varela-Ortega, M. Schlüter, K. Roest, P. Huntjens, F. Jaspers, H. Buiteveld, E. Moreno, J. de Padraza Carrera, R. Slámová, R. Martínková, I. Blanco, P. Esteve, K. Pringle, C. Pahl-Wostl, and P. Kabat, 2010: Cross-comparison of climate change adaptation strategies across large river basins in Europe, Africa and Asia. *Water Resources Management*, **24(14)**, 4121-4160.

Kuruppu, N., 2009: Adapting water resources to climate change in Kiribati: the importance of cultural values and meanings. *Environmental Science & Policy*, **12(7)**, 799-809.

Kuruppu, N. and D. Liverman, 2011: Mental preparation for climate adaptation: the role of cognition and culture in enhancing adaptive capacity of water management in Kirabati. *Global Environmental Change*, **21(2)**, 657-669.

Kwok, A.G. and N.B. Rajkovich, 2010: Addressing climate change in comfort standards. *Building and Environment*, **45(1)**, 18-22.

Kyung-Soo, J., C. Eun-Sung, K. Young-Gyu, and K. Yeonjoo, 2013: A fuzzy multi-criteria approach to flood risk vulnerability in South Korea by considering climate change impacts. *Expert Systems with Applications*, **40(4)**, 1003-1013.

Lafleur, B., D. Pare, A.D. Munson, and Y. Bergeron, 2010: Response of northeastern North American forests to climate change: will soil conditions constrain tree species migration? *Environmental Reviews*, **18**, 279-289.

Lal, P.N., P. Mitchell, P. Aldunce, H. Auld, R. Mechler, A. Miyan, L.E. Romano, and S. Zakaria, 2012: National systems for managing the risks from climate extremes and disasters. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 339-392.

Lal, R., 2011: Soil degradation and food security in South Asia. *Climate Change and Food Security in South Asia*, **4**, 137-152.

Larson, A.M., 2011: Forest tenure reform in the age of climate change: lessons for REDD+. *Global Environmental Change*, **21(2)**, 540-549.

Lata, S. and P. Nunn, 2012: Misperceptions of climate-change risk as barriers to climate-change adaptation: a case study from the Rewa Delta, Fiji. *Climatic Change*, **110**, 169-186.

Lavell, A., M. Oppenheimer, C. Diop, J. Hess, R. Lempert, J. Li, R. Muir-Wood, and S. Myeong, 2012: Climate change: new dimensions in disaster risk, exposure, vulnerability, and resilience. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 25-64.

Lavergne, S., N. Mouquet, W. Thuiller, and O. Ronce, 2010: Biodiversity and climate change: integrating evolutionary and ecological responses of species and communities. *Annual Review of Ecology, Evolution, and Systematics*, **41(1)**, 321-350.

Leary, N., K. Averyt, B. Hewitson, and J. Marengo, 2009: Crossing thresholds in regional climate research: synthesis of the IPCC expert meeting on regional impacts, adaptation, vulnerability, and mitigation. *Climate Research*, **40(2-3)**, 121-131.

Lebel, L., E. Nikitina, C. Pahl-Wostl, and C. Knieper, 2013: Institutional fit and river basin governance: a new approach using multiple composite measures. *Ecology and Society*, **18(1)**, 1, www.ecologyandsociety.org/vol18/iss1/art1/.

Leichenko, R., 2012: Climate change, globalization, and the double exposure challenge to sustainability: rolling the dice in coastal New Jersey. In: *Sustainability Science* [Weinstein, W.P. and R.E. Turner (eds.)]. Springer, New York, NY, USA, pp. 315-328.

Leichenko, R.M., K.L. O'Brien, and W.D. Solecki, 2010: Climate change and the global financial crisis: a case of double exposure. *Annals of the Association of American Geographers*, **100(4)**, 963-972.

Lemieux, C.J., T.J. Beechey, and P.A. Gray, 2011: Prospects for Canada's protected areas in an era of rapid climate change. *Land use Policy*, **28(4)**, 928-941.

Lemos, M.C., C.J. Kirchhoff, and V. Ramprasad, 2012: Narrowing the climate information usability gap. *Nature Climate Change*, **2**, 789-794.

Lemos, M.C., A. Agrawal, H. Eakin, D.R. Nelson, N.L. Engle, and O. Johns, 2013: Building adaptive capacity to climate change in less developed countries. In: *Climate Science for Serving Society* [Asrar, G.R. and J.W. Hurrell (eds.)]. Springer Science, Dordrecht, Netherlands, pp. 437-457.

Lenton, T., H. Held, E. Kriegler, J. Hall, W. Lucht, S. Rahmstorf, and S. Hoachim, 2008: Tipping points in the Earth's climate system. *Proceedings of the National Academy of Sciences of the United States of America*, **105(6)**, 1786-1793.

Lenton, T.M., V.N. Livina, V. Dakos, E.H. Van Nes, and M. Scheffer, 2012: Early warning of climate tipping points from critical slowing down: comparing methods to improve robustness. *Philosophical Transactions of the Royal Society A*, **370(1962)**, 1185-1204.

Lesnikowski, A.C., J.D. Ford, L. Berrang-Ford, M. Barrera, P. Berry, J. Henderson, and S.J. Heymann, 2013: National-level factors affecting planned, public adaptation to health impacts of climate change. *Global Environmental Change*, **23(5)**, 1153-1163.

Levermann, A., J.L. Bamber, S. Drijfhout, A. Ganopolski, W. Haeberli, N.R. Harris, M. Huss, K. Krüger, T.M. Lenton, R.W. Lindsay, D. Notz, P. Wadhams, and S. Weber, 2012: Potential climatic transitions with profound impact on Europe. *Climatic Change*, **110(3-4)**, 845-878.

Levin, K. and B. Petersen, 2011: Tradeoffs in the policy process in advancing climate change adaptation: the case of Australia's Great Eastern Ranges Initiative. *Journal of Natural Resources Policy Research*, **3(2)**, 145-162.

Li, W. and L. Huntsinger, 2011: China's grassland contract policy and its impacts on herder ability to benefit in Inner Mongolia: tragic feedbacks. *Ecology and Society*, **16(2)**, 1, www.ecologyandsociety.org/vol16/iss2/art1/.

Libecap, G.D., 2010: *Institutional Path Dependence in Climate Adaptation: Coman's "Some Unsettled Problems of Irrigation".* NBER Working Paper No. w16324, National Bureau of Economic Research (NBER), Cambridge, MA, USA, 27 pp.

Lieske, D.J., T. Wade, and L.A. Roness, 2013: Climate change awareness and strategies for communicating the risk of coastal flooding: a Canadian Maritime case example. *Estuarine, Coastal and Shelf Science*, www.sciencedirect.com/science/article/pii/S0272771413002035.

Liu, G.Y., Z.F. Yang, and B. Chen, 2012: Energy-based urban dynamic modeling of long-run resource consumption, economic growth and environmental impact: conceptual considerations and calibration. *Procedia Environmental Sciences*, **13**, 1179-1188.

Lobell, D.B., M.B. Burke, C. Tebaldi, M.D. Mastrandrea, W.P. Falcon, and R.L. Naylor, 2008: Prioritizing climate change adaptation needs for food security in 2030. *Science*, **319(5863)**, 607-610.

Lobell, D.B., W. Schlenker, and J. Costa-Roberts, 2011: Climate trends and global crop production since 1980. *Science*, **333(6042)**, 616-620.

Lovejoy, T.E., 2005: Conservation with a changing climate. In: *Climate Change and Biodiversity* [Lovejoy, T. and L. Hannah (eds.)]. Yale University Press, New Haven, CT, USA, pp. 325-328.

Lovejoy, T.E., 2006: Protected areas: a prism for a changing world. *Trends in Ecology & Evolution*, **21**, 329-333.

Lowe, D., K.L. Ebi, and B. Forsberg, 2011: Heatwave early warning systems and adaptation advice to reduce human health consequences of heatwaves. *International Journal of Environmental Research and Public Health*, **8**, 4623-4648.

Lowe, J.A., S.C.B. Raper, S.K. Liddicoat, and L.K. Gohar, 2009: How difficult is it to recover from dangerous levels of global warming? *Environmental Research Letters*, **4**, 014012, doi:10.1088/1748-9326/4/1/014012.

Luzzadder-Beach, S., T.P. Beach, and N.P. Dunning, 2012: Wetland fields as mirrors of drought and the Maya abandonment. *Proceedings of the National Academy of Sciences of the United States of America*, **109(10)**, 3646-3651.

Lybbert, T.J., and D.A. Sumner, 2012: Agricultural technologies for climate change in developing countries: policy options for innovation and technology diffusion. *Food Policy*, **37(1)**, 114-123.

Maibach, E.W., A. Chadwick, D. McBride, M. Chuk, K.L. Ebi, and J. Balbus, 2008: Climate change and local public health in the United States: preparedness, programs and perceptions of local public health department directors. *PLoS One*, **3(7)**, e2838, doi:10.1371/journal.pone.0002838.

Mailhot, A. and S. Duchesne, 2009: Design criteria of urban drainage infrastructures under climate change. *Journal of Water Resources Planning and Management*, **136(2)**, 201-208.

Malhi, Y., L.E.O.C. Aragao, D. Galbraith, C. Huntingford, R. Fisher, P. Zelazowski, S. Sitch, C. McSweeney, and P. Meir, 2009a: Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academies of Sciences of the United States of America*, doi:10.1073/pnas.0804619106.

Malhi, Y., J.T. Roberts, R.A. Betts, T.J. Killeen, W. Li, and C.W. Nobre, 2009b: Climate change, deforestation, and the fate of the Amazon. *Science*, **319(5860)**, 169-172.

Malka, A. and J.A. Krosnick, 2009: The association of knowledge with concern about global warming: trusted information sources shape public thinking. *Risk Analysis*, **29**, 633-647.

Mallick, F.H. and M.A. Rahman, 2007: Cyclone shelters and alternatives for sustained development in Bangladesh. *Journal of South Asia Disaster Studies*, **1(1)**, 59-67.

Mallick, F.H. and A. Rahman, 2013: Cyclone and tornado risk and reduction approaches in Bangladesh. In: *Disaster Risk Reduction Approaches in Bangladesh*. Springer Japan, Osaka, Japan, pp. 91-102.

Mallick, F.H, K.H. Kabir, and M.H. Kabir, 2008: *Improved Design and Construction of Rural Housing in Noakhali*. International Union for Conservation of Nature and Natural Resources (IUCN) Bangladesh Country Office, Dhaka, Bangladesh, 43 pp.

Marshall, N.A., 2010: Understanding social resilience to climate variability in primary enterprises and industries. *Global Environmental Change*, **20**, 36-43.

Marvin, H.J.P., G.A. Kleter, H.J. Van der Fels-Klerx, M.Y. Noordam, E. Franz, D.J.M. Willems, and A. Boxall, 2013: Proactive systems for early warning of potential impacts of natural disasters on food safety: climate-change-induced extreme events as case in point. *Food Control*, **34**, 444-456.

Mastrandrea, M.D. and S.H. Schneider, 2004: Probabilistic integrated assessment of "dangerous" climate change. *Science*, **304(5670)**, 571-575.

Matasci, C., S. Kruse, N. Barawid, and P. Thalmann, 2013: Exploring barriers to climate change adaptation in the Swiss tourism sector. *Mitigation and Adaptation Strategies for Global Change*, doi:10.1007/s11027-013-9471-1.

Matesanz, S., E. Gianoli, and F. Valladares, 2010: Global change and the evolution of phenotypic plasticity in plants. *Annals of the New York Academy of Sciences*, **1206**, 35-55.

Matthews, T., 2013: Institutional perspectives on operationalising climate adaptation through planning. *Planning Theory & Practice*, **14(2)**, 198-210.

Maynard, J., A. Baird, and M. Pratchett, 2008: Revisiting the Cassandra syndrome: the changing climate of coral reef research. *Coral Reefs*, **27**, 745-749.

McAnany, P.A. and N. Yoffee, 2010: Questioning how different societies respond to crises. *Nature*, **464(7291)**, 977-977.

McCright, A.M. and R.E. Dunlap, 2011: The politicization of climate change and polarization in the American public's views of global warming, 2001-2010. *The Sociological Quarterly*, **52(2)**, 155-194.

McDonald, J., 2011: The role of law in adapting to climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **2**, 283-295.

McGray, H., H. Hammill, R. Bradley, E.L. Schipper, and J.E. Parry, 2007: *Weathering the Storm: Options for Framing Adaptation and Development.* World Resources Institute, Washington, DC, USA, 57 pp.

McKune, S.L. and J.A. Silva, 2013: Pastoralists under pressure: double exposure to economic and environmental change in Niger. *The Journal of Development Studies*, **49(12)**, 1711-1727, doi:10.1080/00220388.2013.822067.

McLachlan, J.S., J.J. Hellmann, and M.W. Schwartz, 2007: A framework for debate of assisted migration in an era of climate change. *Conservation Biology*, **21(2)**, 297-302.

McNamara, K. and C. Gibson, 2009: 'We don't want to leave our land': Pacific ambassadors to the United Nations resist the category of 'climate refugees'. *Geoforum*, **40**, 475-483.

McNamara, K.E. and J.P. McNamara, 2011: Using participatory action research to share knowledge of the local environment and climate change: case study of Erub Island, Torres Strait. *The Australian Journal of Indigenous Education*, **40**, 30-39.

McNamara, K.E., S.G. Smithers, R. Westoby, and K. Parnell, 2011: *Limits to Climate Change Adaptation for Low-Lying Communities in the Torres Strait.* National Climate Change Adaptation Research Facility (NCCARF), Griffith University, Gold Coast Campus, Southport, Australia, 87 pp.

Measham, T.G and B.L. Preston, 2012: Vulnerability analysis, risk and deliberation: the Sydney climate change adaptation initiative. In*: Risk and Social Theory in Environmental Management* [Measham T. and S. Lockie (eds.)]. CSIRO Publishing, Collingwood, Australia, pp. 147-157.

Measham, T.G., B.L. Preston, C. Brooke, T.F. Smith, C. Morrison, G. Withycombe, and R. Gorddard, 2011: Adapting to climate change through local municipal planning: barriers and opportunities. *Mitigation and Adaptation Strategies for Global Change*, **16(8)**, 889-909.

Mechler, R. and K.N. Islam, 2013: Cost-benefit analysis of disaster risk management and climate adaptation. In: *The Economic Impacts of Natural Disasters* [Guha-Sapir, D., I. Santos, and A. Borde (eds.)]. Oxford University Press, Oxford, UK, pp. 80-106.

Meera, S.N., V. Balaji, P. Muthuraman, B. Sailaja, and S. Dixit, 2012: Changing roles of agricultural extension: harnessing information and communication technology (ICT) for adapting to stresses envisaged under climate change. In: *Crop Stress and its Management: Perspectives and Strategies* [Venkateswarlu, B., A.K. Shanker, C. Shanker, and M. Maheswari (eds.)]. Springer, Dordrecht, Netherlands, pp. 585-605.

Mees, H.L., P.P. Driessen, and H.A. Runhaar, 2012: Exploring the scope of public and private responsibilities for climate adaptation. *Journal of Environmental Policy & Planning*, **14(3)**, 305-330.

Meinshausen, M., N. Meinshausen, W. Hare, S.C.B. Raper, K. Frieler, R. Knutti, D.J. Frame, and M.R. Allen, 2009: Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature*, **458(7242)**, 1158-1162.

Merz, B., J. Hall, M. Disse, and A. Schumann, 2010: Fluvial flood risk management in a changing world. *Natural Hazards and Earth System Science*, **10(3)**, 509-527.

Meze-Hausken, E., 2008: On the (im-)possibilities of defining human climate thresholds. *Climatic Change*, **89(3-4)**, 299-324.

Meyer, R., 2011: The public values failures of climate science in the US. *Minerva*, **49(1)**, 47-70.

Milfont, T.L. 2012: The interplay between knowledge, perceived efficacy, and concern about global warming and climate change: a one-year longitudinal study. *Risk Analysis*, **32(6),** 1003-1020.

Millar, C.I., N.L. Stephenson, and S.L. Stephens, 2007: Climate change and forests of the future: managing in the face of uncertainty. *Ecological Applications*, **17(8)**, 2145-2151.

Milman, A., L. Bunclark, D. Conway, and W.N. Adger, 2013: Assessment of institutional capacity to adapt to climate change in transboundary river basins. *Climatic Change*, **121(4)**, 755-770.

Mimura, N., L. Nurse, R.F. McLean, J. Agard, L. Briguglio, P. Lefale, R. Payet, and G. Sem, 2007: Small islands. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 687-716.

Montgomery, M.R., 2008: The urban transformation of the developing world. *Science*, **(5864)**, 761-764.

Mooney, C. and P. Tan, 2012: South Australia's River Murray: social and cultural values in water planning. *Journal of Hydrology*, **474**, 29-37.

Moreno, A. and S. Becken, 2009: A climate change vulnerability assessment methodology for coastal tourism. *Journal of Sustainable Tourism*, **17(4)**, 473-488.

Morgan, C.L., 2011: *Limits to Adaptation: A Review of Limitation Relevant to the Project "Building Resilience to Climate Change – Coastal Southeast Asia"*. International Union for Conservation of Nature and Natural Resources (IUCN), Gland, Switzerland, 31 pp.

Morin, X. and W. Thuiller, 2009: Comparing niche-and process-based models to reduce prediction uncertainty in species range shifts under climate change. *Ecology*, **90(5)**, 1301-1313.

Morrison, C. and C. Pickering, 2012: *Limits to Climate Change Adaptation: Case Study of the Australian Alps*. National Climate Change Adaptation Research Facility (NCCARF), Griffith University, Gold Coast Campus, Southport, Australia, 78 pp.

Mortreux, C. and J. Barnett, 2009: Climate change, migration and adaptation in Funafuti, Tuvalu. *Global Environmental Change*, **19**, 105-112.

Moser, B., J.D. Fridley, A.P. Askew, and J.P. Grime, 2011: Simulated migration in a long-term climate change experiment: invasions impeded by dispersal limitation, not biotic resistance. *Journal of Ecology*, **99(5)**, 1229-1236.

Moser, S.C., 2010a: Communicating climate change: history, challenges, process and future directions. *Wiley Interdisciplinary Reviews: Climate Change*, **1(1),** 31-53.

Moser, S.C., 2010b: Now more than ever: the need for more societally-relevant research on vulnerability and adaptation to climate change. *Applied Geography*, **30(4)**, 464-474.

Moser, S.C. and J.A. Ekstrom, 2010: A framework to diagnose barriers to climate change adaptation. *Proceedings of the National Academy of Sciences of the United States of America*, **107(51)**, 22026-22031.

Moss, R.H., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren, T.R. Carter, S. Emori, M. Kainuma, T. Kram, G.A. Meehl, J.F.B., Mitchell, N. Nakicenovic, K. Riahi, S.J. Smith, R.J. Stougger, A.M. Thomson, J.P. Weyant, and T.J. Wilbanks, 2010: The next generation of scenarios for climate change research and assessment. *Nature*, **463**, 747-756.

Mukheibir, P., N. Kuruppu, A. Gero, and J. Herriman, 2013: Overcoming cross-scale challenges to climate change adaptation for local government: a focus on Australia. *Climatic Change*, **121(2)**, 271-283.

Müller, N., W. Kuttler, and A.B. Barlag, 2013: Counteracting urban climate change: adaptation measures and their effect on thermal comfort. *Theoretical and Applied Climatology*, doi:10.1007/s00704-013-0890-4.

Munich Re, 2011: *Great Natural Catastrophes Worldwide 1950 – 2010.* Münchener Rückversicherungs-Gesellschaft, Geo Risks Research, NatCatSERVICE, Munich, Germany.

Murphy, C.F., D. Allen, B. Allenby, J. Crittenden, C.I. Davidson, C. Hendrickson, and H.S. Matthews, 2009: Sustainability in engineering education and research at U.S. universities. *Environmental Science & Technology*, **43(15)**, 5558-5564.

Mustelin, J., R. Klein, B. Assaid, T. Sitari, M. Khamis, A. Mzee, and T. Haji, 2010: Understanding current and future vulnerability in coastal settings: community perceptions and preferences for adaptation in Zanzibar, Tanzania. *Population & Environment*, **31(5)**, 371-398.

Næss, L.O., G. Bang, S. Eriksen, and J. Vevatne, 2005: Institutional adaptation to climate change: flood responses at the municipal level in Norway. *Global Environmental Change*, **15(2)**, 125-138.

Nassopoulos, H., P. Dumas, and S. Hallegatte, 2012: Adaptation to an uncertain climate change: cost benefit analysis and robust decision making for dam dimensioning. *Climatic Change*, **114(3-4)**, 497-508.

National Research Council, 2009: *Informing Decisions in a Changing Climate*. Panel on Strategies and Methods for Climate-Related Decision Support, Committee on the Human Dimensions of Global Change, Division of Behavioral and Social Sciences and Education, National Research Council, The National Academies Press, Washington, DC, USA, 188 pp.

National Research Council, 2010: *Adapting to the Impacts of Climate Change.* America's Climate Choices: Panel on Adapting to Impacts of Climate Change, Division on Earth and Life Studies, National Research Council, The National Academies Press, Washington, DC, USA, 272 pp.

Nelson, R., M. Howden, and M. Stafford Smith, 2008: Using adaptive governance to rethink the way science supports Australian drought policy. *Environmental Science & Policy*, **11(7)**, 588-601.

Nelson, R., P. Kokic, S. Crimp, P. Martin, H. Meinke, and S.M. Howden, 2010a: The vulnerability of Australian rural communities to climate variability and change: part I – conceptualizing and measuring vulnerability. *Environmental Science & Policy*, **13(1)**, 8-17.

Nelson, R., P. Kokic, S. Crimp, P. Martin, H. Meinke, and S.M. Howden, 2010b: The vulnerability of Australian rural communities to climate variability and change: part II – integrating impacts with adaptive capacity. *Environmental Science & Policy*, **13(1)**, 18-27.

New, M., D. Liverman, H. Schroder, and K. Anderson, 2011: Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications. *Philosophical Transactions of the Royal Society A*, **369**, 6-19.

Newton, P.W., 2013: Regenerating cities: technological and design innovation for Australian suburbs. *Building Research and Information*, **41(5)**, 575-588.

Nhemachena, C. and R. Hassan, 2007: *Micro-Level Analysis of Farmers' Adaptation to Climate Change in Southern Africa*. IFPRI Discussion Paper No. 00714, International Food Policy Research Institute (IFPRI), Washington, DC, USA, 30 pp.

Nicholls, R.J., N. Marinova, J.A. Lowe, S. Brown, P. Vellinga, D. De Gusmao, and R.S. Tol, 2011: Sea-level rise and its possible impacts given a 'beyond 4°C world' in the twenty-first century. *Philosophical Transactions of the Royal Society A*, **369(1934**), 161-181.

Nicholls, R., 2007: *Adaptation Options for Coastal Zones and Infrastructure: An Analysis for 2030*. Report to the Financial and Technical Support Division, United Nations Framework Convention on Climate Change (UNFCCC), Bonn, Germany, 35 pp.

Nielsen, J.O. and A. Reenberg, 2010: Cultural barriers to climate change adaptation: a case study from Northern Burkina Faso. *Global Environmental Change*, **20(1)**, 142-152.

Nisbet, M. and D. Scheufele, 2009: What's next for science communication? Promising directions and lingering distractions. *American Journal of Botany*, **96(10)**, 1767-1778.

Nkem, J., F.B. Kalame, M. Idinoba, O.A. Somorin, O. Ndoye, and A. Awono, 2010: Shaping forest safety nets with markets: adaptation to climate change under changing roles of tropical forests in Congo Basin. *Environmental Science & Policy*, **13**, 498-508.

Nordhaus, W.D., 2001: Global warming economics. *Science*, **294(5545)**, 1283-1284.

Norman, L., N. Tallent-Halsell, W. Labiosa, M. Weber, A. McCoy, K. Hirschboeck, J. Callegary, C. Van Riper III, and F. Gray, 2010: Developing an ecosystem services online decision support tool to assess the impacts of climate change and urban growth in the Santa Cruz watershed; where we live, work, and play. *Sustainability*, **2(7)**, 2044-2069.

Nunavut Social Development Council, 1999: On our own terms: the state of Inuit culture and society. In: *Taking Stock: A Review of the First Five Years of Implementing the Nunavut Land Claims Agreement* [Nunavut Social Development Council (ed.)]. Nunavut Tunngavik, Inc., Iqaluit, NU, Canada, pp. 70-97.

O'Brien, K., 2009: Do values subjectively define the limits to climate change adaptation? In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, N.W., I. Lorenzoni, and K. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK, pp. 164-180.

O'Brien, K., 2012: Global environmental change II: from adaptation to deliberate transformation. *Progress in Human Geography*, **36(5)**, 667-676.

O'Brien, K.L. and J. Wolf, 2010: A values-based approach to vulnerability and adaptation to climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **1(2)**, 232-242.

O'Brien, K., M. Pelling, A. Patwardhan, S. Hallegatte, A. Maskrey, T. Oki, U. Oswald-Spring, T. Wilbanks, and P.Z. Yanda, 2012: Toward a sustainable and resilient future. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 437-486.

OHCHR, 2009: *Report of the Office of the United Nations High Commissioner for Human Rights on the Relationship Between Climate Change and Human Rights*. United Nations Document: A/HRC/10/61, Human Rights Council, Tenth Session, the United Nations High Commissioner for Human Rights (OHCHR), United Nations, New York, NY, USA, 32 pp.

O'Hara, J.K., 2012: *Ensuring the Harvest: Crop Insurance and Credit for a Healthy Farm and Food Future*. Union of Concerned Scientists (UCS), Cambridge, MA, USA, 30 pp.

O'Neill, B.C., M. Dalton, R. Fuchs, L. Jiang, S. Pachauri, and K. Zigova, 2010: Global demographic trends and future carbon emissions. *Proceedings of the National Academy of Sciences of the United States of America*, **(41)**, 17521-17523.

O'Neill, S. and J. Handmer, 2012: Responding to bushfire risk: the need for transformative adaptation. *Environmental Research Letters*, **7**, 014018, doi:10.1088/1748-9326/7/1/014018.

O'Neill, S.J. and S. Nicholson-Cole, 2009: "Fear won't do it": promoting positive engagement with climate change through visual and iconic representations. *Science Communication*, **30**, 355-379.

Olesen, J.E., M. Trnka, K.C. Kersebaum, A.O. Skjelvåg, B. Seguin, P. Peltonen-Sainio, F. Rossi, J. Kozyra, and F. Micale, 2011: Impacts and adaptation of European crop production systems to climate change. *European Journal of Agronomy*, **34(2)**, 96-112.

Orlove, B., 2009: Glacier retreat: reviewing the limits of human adaptation to climate change. *Environment*, **51(3)**, 22-34.

Osbahr, H., C. Twyman, W.N. Adger, and D.S.G Thomas, 2010: Evaluating successful livelihood adaptation to climate variability and change in southern Africa. *Ecology and Society*, **15(2)**, 27, www.ecologyandsociety.org/vol15/iss2/art27/.

Ospina, A.V. and R. Heeks, 2010a: *Linking ICTs and Climate Change Adaptation*. Institute for Development Policy and Management, University of Manchester, Manchester, UK, 39 pp.

Ospina, A.V. and R. Heeks, 2010b: *Unveiling the Links between ICTs and Climate Change in Developing Countries: A Scoping Study*. Institute for Development Policy and Management, University of Manchester, Manchester, UK, 59 pp.

Paavola, J. 2008. Livelihoods, vulnerability and adaptation to climate change in Morogoro, Tanzania. *Environmental Science & Policy*, **11(7)**, 642-654.

Paavola, J. and W.N. Adger, 2006: Fair adaptation to climate change. *Ecological Economics*, **56(4)**, 594-609.

Papademetriou, M.K., F.J. Dent, and F.M. Herath (eds.), 2000: *Bridging the Rice Yield Gap in the Asia-Pacific Region*. RAP PUBLICATION: 2000/16, Food and Agricultural Organisation of the United Nations (FAO), Regional Office for Asia and the Pacific, Bangkok, Thailand, 222 pp.

Park, S.E., N.A. Marshall, E. Jakku, A.M. Dowd, S.M. Howden, and A. Fleming, 2012: Informing adaptation responses to climate change through theories of transformation. *Global Environmental Change*, **22(1)**, 115-126.

Parry, M., N. Arnell, P. Berry, D. Dodman, S. Fankhauser, C. Hope, S. Kovats, R. Nicholls, D. Satterthwaite, R. Tiffin, and T. Wheeler, 2009: *Assessing the Costs of Adaptation to Climate Change: A Review of the UNFCCC and Other Recent Estimates*. International Institute for Environment and Development (IIED) and the Grantham Institute for Climate Change, Imperial College, London, UK, 111 pp.

Pasquini, L., R.M. Cowling, and G. Ziervogel, 2013: Facing the heat: barriers to mainstreaming climate change adaptation in local government in the Western Cape Province, South Africa. *Habitat International*, **40**, 225-232.

Patt, A.G. and D. Schröter, 2008: Perceptions of climate risk in Mozambique: implications for the success of adaptation strategies. *Global Environmental Change*, **18(3)**, 458-467.

Patt, A.G., L. Ogallo, and M. Hellmuth, 2007: Learning from 10 years of climate outlook forums in Africa. *Science*, **318(5847)**, 49-50.

Patt, A.G., M. Tadross, P. Nussbaumer, A. Kwabena, M. Metzger, J. Rafael, A. Goujon, and G. Brundri, 2010a: Estimating least-developed countries' vulnerability to climate-related extreme events over the next 50 years. *Proceedings of the National Academy of Sciences of the United States of America*, **107(4)**, 1333-1337.

Patt, A.G., D.P. van Vuuren, F. Berkhout, A. Aaheim, A.F. Hof, M. Isaac, and R. Mechler, 2010b: Adaptation in integrated assessment modeling: where do we stand? *Climatic Change*, **99**, 383-402.

Patz, J.A., H.K. Gibbs, J.A. Foley, J.V. Rogers, and K.R. Smith, 2007: Climate change and global health: quantifying a growing ethical crisis. *EcoHealth*, **4(4)**, 397-405.

Pautasso, M., T.F. Döring, M. Garbelotto, L. Pellis, and M.J. Jeger, 2012: Impacts of climate change on plant diseases – opinions and trends. *European Journal of Plant Pathology*, **133(1)**, 295-313.

Paavola, J., 2011: *Climate Change: The Ultimate 'Tragedy of the Commons'?* Centre for Climate Change Economics and Policy Working Paper No. 53, Sustainability Research Institute Paper No. 24, Center for Climate Change Economics and Policy and Sustainability Research Institute (SRI), SRI, School of Earth and Environment, The University of Leeds, Leeds, UK, 32 pp.

PCAST, 2011: *Sustaining Environmental Capital: Protecting Society and the Economy*. Report to the President, President's Council of Advisors on Science and Technology (PCAST), Executive Office of the President, Washington, DC, USA, 126 pp.

Pearce, T.D., J.D. Ford, G.J. Laidler, B. Smit, F. Duerden, M. Allarut, M. Andrachuk, S. Baryluk, A. Dialla, P. Elee, A. Goose, T. Ikummaq, E. Joamie, F. Kataoyak, E. Loring, S. Meakin, S. Nickels, K. Shappa, J. Shirley, and J. Wandel, 2009: Community collaboration and climate change research in the Canadian Arctic. *Polar Research*, **28(1)**, 10-27.

Pearce, T., H. Wright, R. Notaina, A. Kudlak, B. Smit, J. Ford, and C. Furgal, 2011: Transmission of environmental knowledge and land skills among Inuit men in Ulukhaktok, Northwest Territories, Canada. *Human Ecology*, **39(3)**, 271-288.

Peck, L.S., M.S. Clark, S.A. Morley, A. Massey, and H. Rossetti, 2009: Animal temperature limits and ecological relevance: effects of size, activity and rates of change. *Functional Ecology*, **23(2)**, 248-256.

Pederson, N., A.R. Bell, T.A. Knight, C. Leland, N. Malcomb, K.J. Anchkaitis, K. Tackett, J. Scheff, A. Brice, B. Catron, W. Blozan, and J. Riddle, 2012: A long-term perspective on a modern drought in the American Southwest. *Environmental Research Letters*, **7**, 014034, doi:10.1088/1748-9326/7/1/014034.

Pelling, M. 2010: *Adaptation to Climate Change: From Resilience to Transformation*. Routledge, Abingdon, UK and New York, NY, USA, 224 pp.

Peters, G.P., R.M. Andrew, T. Boden, J.G. Canadell, P. Ciais, C. Le Quere, G. Marland, M.R. Raupach, and C. Wilson, 2013: The challenge to keep global warming below 2 °C. *Nature Climate Change*, **3**, 4-6.

Pfister, S., A. Koehler, and S. Hellweg, 2009: Assessing the environmental impacts of freshwater consumption in LCA. *Environmental Science & Technology*, **43(11)**, 4098-4104.

Pfister, S., P. Bayer, A. Koehler, and S. Hellweg, 2011a: Environmental impacts of water use in global crop production: hotspots and trade-offs with land use. *Environmental Science & Technology*, **45(13)**, 5761-5768.

Pfister, S., P. Bayer, A. Koehler, and S. Hellweg, 2011b: Projected water consumption in future global agriculture: scenarios and related impacts. *Science of the Total Environment*, **409(20)**, 4206-4216.

Piao, S., P. Ciais, Y. Huang, Z. Shen, S. Peng, J. Li, L. Zhou, H. Liu, Y. Ma, Y. Ding, P. Friedlingstein, C. Liu, K. Tan, Y. Yu, T. Zhang, and J. Fang, 2010: The impacts of climate change on water resources and agriculture in china. *Nature*, **467**, 43-51.

Pidgeon, N., 2012: Climate change risk perception and communication: addressing a critical moment? *Risk Analysis*, **32(6)**, 951-956.

Pidgeon, N. and C. Butler, 2009: Risk analysis and climate change. *Environmental Politics*, **18(5)**, 670-688.

Pidgeon, N. and B. Fischhoff, 2011: The role of social and decision sciences in communicating uncertain climate risks. *Nature Climate Change*, **1(1)**, 35-41.

Pielke Jr., R.A., 2007: Future economic damage from tropical cyclones: sensitivities to societal and climate changes. *Philosophical Transactions of the Royal Society A*, **365**, 2717-2729.

Pielke Jr., R.A., J. Gratz, C.W. Landsea, D. Collins, M.A. Saunders, and R. Musulin, 2008: Normalized hurricane damages for the United States: 1900-2005. *Natural Hazards Review*, **9(1)**, 29-42.

Pini, B., S. Wild River, and F.M.H. McKenzie, 2007: Factors inhibiting local government engagement in environmental sustainability: case studies from rural Australia. *Australian Geographer*, **38(2)**, 161-175.

Pinto, R. and F.C. Martins, 2013: The Portuguese national strategy for integrated coastal zone management as a spatial planning instrument to climate change adaptation in the Minho River Estuary (Portugal NW-Coastal Zone). *Environmental Science and Policy*, **33**, 76-96.

Pittock, J., 2011: National climate change policies and sustainable water management: conflicts and synergies. *Ecology and Society*, **16(2)**, 25, www.ecologyand society.org/vol16/iss2/art25/.

Pittock, J., 2013: Lessons from adaptation to sustain freshwater environments in the Murray-Darling Basin, Australia. *Wiley Interdisciplinary Reviews: Climate Change*, **4**, 429-438.

Pray, C., L. Nagarajan, L. Li, J. Huang, R. Hu, K.N. Selvaraj, O. Napasintuwong, and R. Chandra, 2011: Potential impact of biotechnology on adaptation of agriculture to climate change: the case of drought tolerant rice breeding in Asia. *Sustainability*, **3**, 1723-1741.

Preston, B.L. 2009: Equitable climate policy in a dangerous world. In: *Climate Change and Social Justice* [Moss, J. (ed.)]. Melbourne University Press, Melbourne, Australia, pp. 224-245.

Preston, B.L, 2013: Local path dependence of U.S. socioeconomic exposure to climate extremes and the vulnerability commitment. *Global Environmental Change*, **23(4)**, 719-732.

Preston, B.L. and Jones, R.N., 2008: Evaluating sources of uncertainty in Australian runoff projections. *Advances in Water Resources*, **31(5)**, 758-775.

Preston, B.L. and M. Stafford Smith, 2009: *Framing Vulnerability and Adaptive Capacity Assessment.* CSIRO Climate Adaptation Flagship Working Paper No. 2, Clayton, VIC, Australia, 52 pp.

Preston, B.L., R.M. Westaway, and E.J. Yuen, 2011a: Climate adaptation planning in practice: an evaluation of adaptation plans from three developed nations. *Mitigation and Adaptation Strategies for Global Change*, **16(4)**, 407-438.

Preston, B.L., E.J. Yuen, and R.M. Westaway, 2011b: Putting climate vulnerability on the map: a critical look at approaches, benefits, and risks. *Sustainability Science*, **6(2)**, 177-202.

Preston, B.L., K. Dow, and F. Berkhout, 2013a: The climate adaptation frontier. *Sustainability*, **5**, 1011-1035.

Preston, B.L., J. Mustelin, and M.C. Maloney, 2013b: Climate adaptation heuristics and the science/policy divide. *Mitigation and Adaptation Strategies for Global Change*, doi:10.1007/s11027-013-9503-x.

Preston, B.L., L. Rickards, S. Dessai, and R. Meyer, 2013c: Water, seas, and wine: science for successful adaptation. In: *Successful Adaptation to Climate Change* [Moser, S. and M. Boykoff (eds.)]. Routledge, Abingdon, UK and New York, NY, USA, pp. 151-169.

Productivity Commission, 2009: *Government Drought Support*. Report, No. 46, Australian Government, Productivity Commission Final Inquiry Report, Melbourne, VIC, Australia, 486 pp.

Ragen, T.J., H.P. Huntington, G. Hovelsrud, and K. Grete, 2008: Conservation of Arctic marine mammals faced with climate change. *Ecological Applications*, **18(2 Suppl.)**, S166-S174.

Rayner, T. and A. Jordan, 2010: Adapting to climate change: an emerging European policy? In: *Climate Change Policy in the European Union: Confronting the Dilemmas of Mitigation and Adaptation* [Jordan, A., D. Huitema, H. van Asselt, T. Rayner, and F. Berhout (eds.)]. Cambridge University Press, Cambridge, UK, pp. 145-166.

Raudsepp-Hearne, C., G.D. Peterson, M. Tengo, E.M. Bennett, T. Holland, K. Benessaiah, G.K. MacDonald, and L. Pfeifer, 2010: Untangling the environmentalist's paradox: why is human well-being increasing as ecosystem services degrade? *BioScience*, **60(8)**, 576-589.

Ren, Z., Z. Chen, and X. Wang, 2011: Climate change adaptation pathways for Australian residential buildings. *Building and Environment*, **46(11)**, 2398-2412.

Renn, O., 2008: *Risk Governance: Coping with Uncertainty in a Complex World.* Earthscan, London, UK, 368 pp.

Renn, O., 2011: The social amplification/attenuation of risk framework: application to climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **2(2)**, 154-169.

Renn, O. and A. Klinke, 2013: A framework of adaptive risk governance for urban planning. *Sustainability*, **5**, 2036-2059.

Roberts, D., R. Boon, N. Diederichs, E. Douwes, N. Govender, A. Mcinnes, and M. Spires, 2012: Exploring ecosystem-based adaptation in Durban, South Africa: "learning-by-doing" at the local government coal face. *Environment and Urbanization*, **24(1)**, 167-195.

Rockström, J., W. Steffen, K. Noone, A. Persson, F.S. Chapin, E.F. Lambin, T.M. Lenton, M. Scheffer, C. Folke, H.J. Schellnhuber, B. Nykvist, C.A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sorlin, P.K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R.W. Corell, V.J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J.A. Foley, 2009: A safe operating space for humanity. *Nature*, **461(7263)**, 472-475.

Rodima-Taylor, D., M.F. Olwig, and N. Chhetri, 2012: Adaptation as innovation, innovation as adaptation: an institutional approach to climate change. *Applied Geography*, **33**, 107-111.

Rogelj, J., W. Hare, J. Lowe, D.P. van Vuuren, K. Riahi, B. Matthews, T. Hanaoka, K. Jian, and M. Meinshausen, 2011: Emission pathways consistent with a 2°C global temperature limit. *Nature Climate Change*, **1(8)**, 413-418.

Romieu, E., T. Welle, S. Schneiderbauer, M. Pelling, and C. Vinchon, 2010: Vulnerability assessment within climate change and natural hazard contexts: revealing gaps and synergies through coastal applications. *Sustainability Science*, **5(2)**, 159-170.

Rosenau, J.N., 2005: Strong demand, huge supply: governance in an emerging epoch. In: *Multi-level Governance* [Bache, I. and M. Flinders (eds.)]. Oxford University Press, Oxford, UK, pp. 31-48.

Rosen, A.M. and I. Rivera-Collazo, 2012: Climate change, adaptive cycles, and the persistence of foraging economies during the late Pleistocene/Holocene transition in the Levant. *Proceedings of the National Academy of Sciences of the United States of America*, **109(10)**, 3640-3645.

Rosenberg, E.A., P.W. Keys, D.B. Booth, D. Hartley, J. Burkey, A.C. Steinemann, and D.P. Lettenmaier, 2010: Precipitation extremes and the impacts of climate change on stormwater infrastructure in Washington State. *Climatic Change*, **102(1-2)**, 319-349.

Rübbelke, D.T.G., 2011: International support of climate change policies in developing countries: strategic, moral and fairness aspects. *Ecological Economics*, **70**, 1470-1480.

Rupp-Armstrong, S. and R. Nicholls 2007: Coastal and estuarine retreat: a comparison of the application of managed realignment in England and Germany. *Journal of Coastal Research*, **236**, 1418-1430.

Rygaard, M., P.J. Binning, and H.-J. Albrechtsen, 2011: Increasing urban water self-sufficiency: new era, new challenges. *Journal of Environmental Management*, **92**, 185-194.

Sathaye, J., A. Najam, C. Cocklin, T. Heller, F. Lecocq, J. Llanes-Regueiro, J. Pan, G. Petschel-Held, S. Rayner, J. Robinson, R. Schaeffer, Y. Sokona, R. Swart, and H. Winkler, 2007: Sustainable development and mitigation. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 691-743.

Schipper, E.L.F., 2008: Religion and risk: the challenge of harnessing faith and reducing exposure. In: *Proceedings of Living with Climate Change: Are There Limits to Adaptation? 7- 8 February 2008, the Royal Geographical Society in London*. The Tyndall Centre for Climate Change Research and the University of Oslo, with the support of the Global Environmental Change and Human Security (GECHS) project, The Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, UK, www.tyndall.ac.uk/events/2008/are-there-limits-adaptation.

Schilling, J., K.P. Freier, E. Hertig, and J. Scheffran, 2012: Climate change, vulnerability and adaptation in North Africa with focus on Morocco. *Agriculture, Ecosystems and Environment*, **156**, 12-26.

Schneider, S.H. and J. Lane, 2006a: An overview of 'dangerous' climate change. In: *Avoiding Dangerous Climate Change* [Schellnhuber, H.J., W. Cramer, N. Nakicenovic, T. Wigley, and G. Yohe (eds.)]. Cambridge University Press, Cambridge, UK, pp. 159-176.

Schneider, S.H. and J. Lane, 2006b: Dangers and thresholds in climate change and the implications for justice. In: *Fairness in Adaptation to Climate Change* [Adger, W.N., J. Paavola, S. Huq, and M.J. Mace (eds.)]. Cambridge University Press, Cambridge, UK, pp. 23-52.

Schneider, S.H., S. Semenov, A. Patwardhan, I. Burton, C.H.D. Magadza, M. Oppenheimer, A.B. Pittock, A. Rahman, J.B. Smith, A. Suarez, and F. Yamin, 2007: Assessing key vulnerabilities and the risk from climate change. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 779-810.

Schweizer, V.J. and B.C. O'Neill, 2013: Systematic construction of global socioeconomic pathways using internally consistent element combinations. *Climatic Change*, doi:10.1007/s10584-013-0908-z.

Scott, D., G. McBoyle, A. Minogue, and B. Mills, 2006: Climate change and the sustainability of ski-based tourism in eastern North America: a reassessment. *Journal of Sustainable Tourism*, **14(4)**, 376-398.

Seidl, R. and M.J Lexer, 2013: Forest management under climatic and social uncertainty: trade-offs between reducing climate change impacts and fostering adaptive capacity. *Journal of Environmental Management*, **114**, 461-469.

Seneviratne, S.I., N. Nicholls, D. Easterling, C.M. Goodess, S. Kanae, J. Kossin, Y. Luo, J. Marengo, K. McInnes, M. Rahimi, M. Reichstein, A. Sorteberg, C. Vera, and X. Zhang, 2012: Changes in climate extremes and their impacts on the natural physical environment. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 109-230.

Sehring, J., 2007: Irrigation reform in Kyrgyzstan and Tajikistan. *Irrigation and Drainage Systems*, **21**, 277-290.

Shah, T., 2009: Climate change and groundwater: India's opportunities for mitigation and adaptation. *Environmental Research Letters*, **4**, 035005, doi:10.1088/1748-9326/4/3/035005.

Shaw, R. and J. Etterson, 2012: Rapid climate change and the rate of adaptation: insight from experimental quantitative genetics. *The New Phytologist*, **195(4)**, 752-765.

Sheehan, P., R.N. Jones, A. Jolley, B.L. Preston, M. Clarke, P.J. Durack, S.M.N. Islam, and P.H. Whetton, 2008: Climate change and the new world economy: implications for the nature and timing of policy responses. *Global Environmental Change*, **18(3)**, 380-396.

Shen, L.Y., J.J. Ochoa, M.N. Shah, and X. Zhang, 2011: The application of urban sustainability indicators – a comparison between various practices. *Habitat International*, **35**, 17-29.

Shen, Y., T. Oki, N. Utsumi, S. Kanae, and N. Hansaki, 2008: Projection of future world water resources under SRES scenarios: water withdrawal. *Hydrological Sciences Journal*, **53(1)**, 11-33.

Sheppard, S.R., A. Shaw, D. Flanders, S. Burch, A. Wiek, J. Carmichael, and S. Cohen, 2011: Future visioning of local climate change: a framework for community engagement and planning with scenarios and visualisation. *Futures*, **43(4)**, 400-412.

Sheridan, S.C., 2007: A survey of public perception and response to heat warnings across four North American cities: an evaluation of municipal effectiveness. *Journal of Biometeorology*, **52**, 3-15.

Silva, J.A., S. Eriksen, and Z.A. Ombe, 2010: Double exposure in Mozambique's Limpopo River basin. *The Geographical Journal*, **176(1)**, 6-24.

Smit, B., I. Burton, R.J.T. Klein, and J. Wandel, 1999: The science of adaptation: a framework for assessment. *Mitigation and Adaptation Strategies for Global Change*, **4**, 199-213.

Smit, B., O. Pilifisofa, I. Burton, B. Challenger, S. Huq, R.J.T. Klein, and G. Yohe, 2001: Adaptation to climate change in the context of sustainable development and equity. In: *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Smit, B., O. Pilifosova, I. Burton, B. Challenger, S. Huq, R.J.T. Klein, and G. Yohe (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 877-912.

Smith, J.B., S.H. Schneider, M. Oppenhimer, G.W. Yohe, W. Haref, M.D. Mastrandrea, A. Patwardhang, I. Burton, J. Corfee-Morloti, C.H.D. Magadzaj, H. Füssel, A.B. Pittock, A. Rahman, A. Suarez, and J.-P. van Yperselen, 2009a: Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) "reasons for concern". *Proceedings of the National Academy of Sciences of the United States of America*, **106(11)**, 4133-4137.

Smith, J.B., J.M. Vogel, and J.E. Cromwell, 2009b: An architecture for government action on adaptation to climate change. An editorial comment. *Climatic Change*, **95(1-2)**, 53-61.

Smith, T.F., C. Brooke, T.G. Measham, B.L. Preston, R. Gorddard, G. Withycombe, B. Beveridge, and C. Morrison, 2008: *Case Studies of Adaptive Capacity: Systems Approach to Regional Climate Change Adaptation Strategies.* Sydney Coastal Councils Group, Inc., Sydney, New South Wales, Australia, 108 pp.

Smith, T.F., R.W. Carter, P. Daffara, and N. Keys, 2010: *The Nature and Utility of Adaptive Capacity Research.* National Climate Change Adaptation Research Facility (NCCARF), Griffith University, Gold Coast Campus, Southport, Australia, 68 pp.

Somero, G.N., 2010: The physiology of climate change: how potentials for acclimatization and genetic adaptation will determine 'winners' and 'losers'. *The Journal of Experimental Biology*, **213(6)**, 912-920.

Sorte, C.J., S.J. Jones, and L.P. Miller, 2011: Geographic variation in temperature tolerance as an indicator of potential population responses to climate change. *Journal of Experimental Marine Biology and Ecology*, **400(1)**, 209-217.

Sosa-Rodriguez, F.S., 2010: Impacts of water management decisions on the survival of a city: from ancient Tenochtitlan to modern Mexico City. *Journal of Water Resources Development*, **27(4)**, 667-689.

Sosa-Rodriguez, F.S., 2013: From federal to city mitigation and adaptation: climate change policy in Mexico City. *Mitigation and Adaptation Strategies for Global Change*, doi:10.1007/s11027-013-9455-1.

Sowers, J., A. Vengosh, and E. Weinthal, 2011: Climate change, water resources, and the politics of adaptation in the Middle East and North Africa. *Climatic Change*, **104(3-4)**, 599-627.

Sovacool, B.K., 2012: Perceptions of climate change risks and resilient island planning in the Maldives. *Mitigation and Adaptation Strategies for Global Change*, **17**, 731-752.

Spies, T.A., T.W. Giesen, F.J. Swanson, J.F. Franklin, D. Lach, and K.N. Johnson, 2010: Climate change adaptation strategies for federal forests of the Pacific Northwest, USA: ecological, policy, and socio-economic perspectives. *Landscape Ecology*, **25(8)**, 1185-1199.

Stafford Smith, M., L. Horrocks, A. Harvey, and C. Hamilton, 2011: Rethinking adaptation for a 4°C world. *Philosophical Transactions of the Royal Society A*, **369**, 196-216.

Steenberg, J.W.N., P.N. Duinker, and P.G. Bush, 2011: Exploring adaptation to climate change in the forests of central Nova Scotia, Canada. *Forest Ecology and Management*, **262**, 2316-2327.

Steffen, W., A. Burbidge, L. Hughes, R. Kitching, D. Lindenmayer, W. Musgrave, M. Stafford Smith, and P. Werner, 2009: *Australian Biodiversity and Climate Change.* CSIRO Publishing, Collingwood, Australia, 248 pp.

Stern, N., S. Peters, V. Bakhshi, A. Bowen, C.S. Cameron, C.D. Catovsky, S. Cruickshank, S. Dietz, N. Edmondson, S. Garbett, L. Hamid, G. Hoffman, D. Ingram, B. Jones, N. Patmore, H. Radcliffe, R. Sathiyarajah, M.C. Stock, V.T. Taylor, H. Wanjie, and D. Zenghelis, 2006: *Stern Review on the Economics of Climate Change.* Cambridge University Press, Cambridge, UK, 579 pp.

Stillwell, A.S., M.E. Clayton, and M.E. Webber, 2011: Technical analysis of a river basin-based model of advanced power plant cooling technologies for mitigating water management challenges. *Environmental Research Letters*, **6**, 034015, doi:10.1088/1748-9326/6/3/034015.

Stoutenborough, J.W. and A. Vedlitz, 2013: The effect of perceived and assessed knowledge of climate change on public policy concerns: an empirical comparison. *Environmental Science & Policy*, doi:10.1016/j.envsci.2013.08.002.

Streeter, R., A.J. Dugmore, and O. Vesteinsson, 2012: Plague and landscape resilience in premodern Iceland. *Proceedings of the National Academy of Sciences of the United States of America*, **109(10)**, 3664-3669.

Stuart-Hill, S. and R.E. Schulze, 2010: Does South Africa's water law and policy allow for climate change adaptation? *Climate and Development*, **2(2)**, 128-144.

Sundblad, E.L., A. Biel, and T. Gärling, 2009: Knowledge and confidence in knowledge about climate change among experts, journalists, politicians, and laypersons. *Environment and Behavior*, **41(2)**, 281-302.

Svenning, J.C. and B. Sandel, 2013: Disequilibrium vegetation dynamics under future climate change. *American Journal of Botany*, doi:10.3732/ajb.1200469.

Svobodová, E., M. Trnka, M. Dubrovský, D. Semerádová, J. Eitzinger, P. Štěpánek, and Z. Žalud, 2013: Determination of areas with the most significant shift in pests' persistence in Europe under climate change. *Pest Management Science*, doi:10.1002/ps.3622.

Sydneysmith, R., M. Andrachuk, B. Smit, and G.K. Hovelsrud, 2010: Vulnerability and adaptive capacity in Arctic communities. In: *Adaptive Capacity and Environmental Governance* [Armitage, D. and R. Plummer (eds.)]. Springer, Berlin Heidelberg, Germany, pp. 133-156.

Svenning, J.C. and B. Sandel, 2013: Disequilibrium vegetation dynamics under future climate change. *American Journal of Botany*, **100(7)**, doi:10.3732/ajb.1200469.

Tal, A., 2011: The desalination debate – lessons learned thus far. *Environment: Science and Policy for Sustainable Development*, **53(5)**, 34-48.

Tan, P.L., K.H. Bowmer, and J. Mackenzie, 2012: Deliberative tools for meeting the challenges of water planning in Australia. *Journal of Hydrology*, **474**, 2-10.

Tao, F., Z. Zhang, and M. Yokozawa, 2011: Dangerous levels of climate change for agricultural production in China. *Regional Environmental Change*, **11(1)**, 41-48.

Taylor, B.M., B.P. Harman, S. Heyenga, and R.R.J. McAllister, 2012: Property developers and urban adaptation: conceptual and empirical perspectives on governance. *Urban Policy and Research*, **30(1)**, 5-24.

Termeer, C., R. Biesbroek, and M. van den Brink, 2012: Institutions for adaptation to climate change: comparing national adaptation strategies in Europe. *European Political Science*, **11**, 41-53.

Thackeray, S.J., T.H. Sparks, M. Frederiksen, S. Burthe, P.J. Bacon, J.R. Bell, M.S. Botham, T.M. Brereton, P.W. Bright, L. Carvalho, T. Clutton-Brock, A. Dawson, M. Edwards, J.M. Elliott, R. Harrington, D. Johns, I.D. Jones, J.T. Jones, D.I. Leech, D.B. Roy, W.A. Scott, M. Smith, R.J. Smithers, I.J. Winfield, and S. Wanless, 2010: Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. *Global Change Biology*, **116(2)**, 3304-3313.

Thomas, C.D., 2010: Climate, climate change and range boundaries. *Diversity and Distributions*, **16(3)**, 488-495.

Thomas, D.S.G. and C. Twyman, 2005: Equity and justice in climate change adaptation amongst natural-resource-dependent societies. *Global Environmental Change*, **15(2)**, 115-124.

Thompson, L.G., E. Mosley-Thompson, M.E. Davis, K.A. Henderson, H.H. Brecher, V.S. Zagorodnov, T.A. Mashiotta, P.N. Lin, V.N. Mikhalenko, D.R. Hardy, and J. Beer, 2002: Kilimanjaro ice core records: evidence of Holocene climate change in tropical Africa. *Science*, **298(5593)**, 589-593.

Thornton, P.K., P.G. Jones, T. Owiyo, R.L. Kruska, M. Herrero, V. Orindi, S. Bhadwal, P Kristjanson, A. Notenbaert, N. Bekele, and A. Omolo, 2008. Climate change and poverty in Africa: mapping hotspots of vulnerability. *African Journal of Agricultural and Resource Economics*, **2(1)**, 24-44.

Thornton, P.K., P. Jones, P. Ericksen, and A. Challinor, 2011: Agriculture and food systems in sub-Saharan Africa in a 4°C+ world. *Philosophical Transactions of the Royal Society A*, **369(1934)**, 117-136.

Tilman, D., C. Balzer, J. Hill, and B.L. Befort, 2011: Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, **108(50)**, 20260-20264.

Timmer, C.P., 2010: *The Changing Role of Rice in Asia's Food Security*. ADB Sustainable Development Working Paper Series No. 15, Asian Development Bank (ADB), Manila, Phillipines, 26 pp.

Timmerman, J.G., S. Koeppel, F. Bernardini, and J.J. Buntsma, 2011: Adaptation to climate change: challenges for transboundary water management. In: *The Economic, Social, and Political Elements of Climate Change* [Filho, W.L. (ed.)]. Springer-Verlag, Berlin Heidelberg, Germany, pp. 523-541.

Titus, J.G., 2011: *Rolling Easements*. EPA 430R11001, U.S. Environmental Protection Agency (EPA), Washington, DC, USA, 169 pp.

Titus, J.G., D.E. Hudgens, D.L. Trescott, M. Craghan, W.H. Nuckols, C.H. Hershner, J.M. Kassakian, C.J. Linn, P.G. Merritt, T.M. McCue, J.F. O'Connell, J. Tanski, and J. Wang, 2009: State and local governments plan for development of most land vulnerable to rising sea level along the US Atlantic coast. *Environmental Research Letters*, **4**, 044008, doi:10.1088/1748-9326/4/4/044008.

Tobey, J., P. Rubinoff, D. Robadue Jr., G. Ricci, R. Volk, J. Furlow, and G. Anderson, 2010: Practicing coastal adaptation to climate change: lessons from integrated coastal management. *Coastal Management*, **38(3)**, 317-335.

Tol, R.S.J. and G.W. Yohe, 2007: The weakest link hypothesis for adaptive capacity: an empirical test. *Global Environmental Change*, **17(2)**, 218-227.

Tol, R.S.J., R.J.T. Klein, and R.J. Nicholls, 2008: Toward successful adaptation to sea-level rise along Europe's coast. *Journal of Coastal Research*, **242**, 432-442.

Tomanek, L., 2010: Variation in the heat shock response and its implication for predicting the effect of global climate change on species' biogeographical distribution ranges and metabolic costs. *The Journal of Experimental Biology*, **213(6)**, 971-979.

Tompkins, E.L. and H. Eakin, 2012: Managing private and public adaptation to climate change. *Global Environmental Change*, **22**, 3-11.

Tompkins, E.L., W.N. Adger, E. Boyd, S. Nicholson-Cole, K. Weatherhead, and N. Arnell, 2010: Observed adaptation to climate change: UK evidence of transition to a well-adapting society. *Global Environmental Change*, **20(4)**, 627-635.

Towler, E., V.A. Saab, R.S. Sojda, K. Dickinson, C.L. Bruyere, and K.R. Newlon, 2012: A risk-based approach to evaluating wildlife demographics for management in a changing climate: a case study of the Lewis's woodpecker. *Environmental Management*, **50**, 1152-1163.

Trærup, S.L, 2012: Informal networks and resilience to climate change impacts: a collective approach to index insurance. *Global Environmental Change*, **22(1)**, 255-267.

Travis, W.R., 2010: Going to extremes: propositions on the social response to severe climate change. *Climatic Change*, **98**, 1-19.

Travis, W.R. and M.T. Huisenga, 2013: The effect of rate of change, variability, and extreme events on the pace of adaptation to a changing climate. *Climatic Change*, **121**, 209-222, doi:10.1007/s10584-013-0876-3.

Tribbia, J. and S.C. Moser, 2008: More than information: what coastal managers need to plan for climate change. *Environmental Science & Policy*, **11(4)**, 315-328.

UKCIP, 2011: *Making Progress: UKCIP & Adaptation in the UK*. UK Climate Impacts Programme (UKCIP), Oxford, UK, 99 pp.

UN DESA Population Division, 2011: *World Population Prospects: The 2010 Revision. CD-ROM Edition – Extended Dataset in Excel and ASCII Formats.* United Nations Department of Economic and Social Affairs (UN DESA) Population Division, New York, NY, USA.

UNEP, 2007: *Global Environment Outlook GEO4: Environment for Development*. United Nations Environment Programme (UNEP), Nairobi, Kenya, 540 pp.

UNEP, 2011: *A Practical Framework for Planning Pro-Development Climate Policy.* United Nations Environment Programme (UNEP), Nairobi, Nigeria, 143 pp.

UNFCCC, 1992: *United Nations Framework Convention on Climate Change.* FCCC/INFORMAL/84, UNFCCC Secretariat, Bonn, Germany, 24 pp.

UNFCCC, 2006: *Application of Environmentally-Sound Technologies for Climate Change Adaptation*. Climate Change Secretariat, United Nations Framework Convention on Climate Change (UNFCCC), Bonn, Germany, 107 pp.

UNFCCC, 2007a: *Investment and Financial Flows to Address Climate Change.* Climate Change Secretariat, United Nations Framework Convention on Climate Change (UNFCCC), Bonn, Germany, 272 pp.

UNFCCC, 2007b: *Report of the Conference of the Parties on Its Sixteenth Session, Held in Bali from 3 to 15 December 2007. Part Two: Action Taken by the Conference of the Parties at Its Thirteenth Session. Decisions Adopted by the Conference of the Parties*. FCCC/CP/2007/6/Add.1, United Nations Framework Convention on Climate Change (UNFCCC) Secretariat, Bonn, Germany, 60 pp.

UNFCCC, 2010: *Adaptation Assessment, Planning and Practice. An Overview from the Nairobi Work Programme on Impacts, Vulnerability and Adaptation to Climate Change.* United Nations Framework Convention on Climate Change (UNFCCC) Secretariat, Bonn, Germany, 77 pp.

UNFCCC, 2011: *Report of the Conference of the Parties on Its Sixteenth Session, Held in Cancun from 29 November to 10 December 2010. Part Two: Action Taken by the Conference of the Parties at Its Sixteenth Session. Decisions Adopted by the Conference of the Parties*. FCCC/CP/2010/7/Add.1, United Nations Framework Convention on Climate Change (UNFCCC) Secretariat, Bonn, Germany, 31 pp.

UNISDR, 2009: *2009 Global Assessment Report on Disaster Risk Reduction: Risk and Poverty in a Changing Climate – Invest Today for a Safer Tomorrow*. United Nations International Strategy for Disaster Reduction (UNISDR), Geneva, Switzerland, 207 pp.

UNISDR, 2011: *2011 Global Assessment Report on Disaster Risk Reduction: Revealing Risk, Redefining Development*. United Nations International Strategy for Disaster Reduction (UNISDR), Geneva, Switzerland, 178 pp.

Urwin, K. and A. Jordan, 2008: Does public policy support or undermine climate change adaptation? Exploring policy interplay across different scales of governance. *Global Environmental Change*, **18**, 180-191.

US GAO, 2009: *Alaska Native Villages. Limited Progress Has Been Made on Relocating Villages Threatened by Flooding and Erosion*. U.S. Government Accountability Office (US GAO), Washington, DC, USA, 53 pp.

USCTI, 2013: *Climate Change Adaptation for Coral Triangle Communities: Guide for Vulnerability Assessment and Local Early Action Planning (LEAP Guide).* U.S. Coral Triangle Initiative Support Program (USCTI), Bangkok, Thailand, 144 pp.

van Aalst, M.K., T. Cannon, and I. Burton, 2008: Community level adaptation to climate change: the potential role of participatory community risk assessment. *Global Environmental Change*, **18**, 165-179.

van den Berg, M.M., W.M. Lafferty, and F.J. Coenen, 2010: Adaptation to climate change induced flooding in Dutch municipalities. In: *The Social and Behavioural Aspects of Climate Change: Linking Vulnerability, Adaptation and Mitigation* [Chang, C.T. (ed.)]. Greenleaf Publishing Limited, Sheffield, UK, 130-156.

van Koningsveld, M., J.P.M. Mulder, M.J.F. Stive, L. Vandervalk, and A.W. Vanderweck, 2008: Living with sea-level rise and climate change: a case study of the Netherlands. *Journal of Coastal Research*, **24**, 367-379.

van Nieuwaal, K., P. Driessen, T. Spit, and C. Termeer, 2009: *A State of the Art Governance Literature on Adaptation to Climate Change: Towards a Research Agenda.* KfC Report No. KfC 003/2009, National Research Programme Knowledge for Climate (KfC), Utrecht, Netherlands, 43 pp.

van Ruijven, B.J., M.A. Levy, A. Agrawal, F. Biermann, J. Birkmann, T.R. Carter, and V.J. Schweizer, 2013: Enhancing the relevance of Shared Socioeconomic Pathways for climate change impacts, adaptation and vulnerability research. *Climatic Change*, doi:10.1007/s10584-013-0931-0.

van Vuuren, D.P., K. Riahi, R. Moss, J. Edmonds, A. Thomson, N. Nakicenovic, T. Kram, F. Berkhout, R. Swart, A. Janetos, S.K. Rose, and N. Arnell, 2012: A proposal for a new scenario framework to support research and assessment in different climate research communities. *Global Environmental Change*, **22(1)**, 21-35.

Verdon-Kidd, D.C., A.S. Kiem, and E.K. Austin, 2012: *Decision Making under Uncertainty – Bridging the Gap between End User Needs and Climate Science Capability*. National Climate Change Adaptation Research Facility (NCCARF), Griffith University, Gold Coast Campus, Southport, Australia, 126 pp.

Verheyen, R., 2005: *Climate Change Damage and International Law: Prevention Duties and State Responsibility*. Brill Academic Publishers, Leiden, Netherlands, 418 pp.

Vermeulen S.J., P.K. Aggarawal, A. Ainslie, C. Angelone, B.M. Campbell, A.J. Challinor, J.W. Hansen, J.S.I. Ingraham, A. Jarvis, P. Kristjanson, C. Lau, G.C. Nelson, P.K. Thornton, P. Kristjanson, C. Lau, G.C. Nelson, P.K. Thornton, and E. Wollenberg, 2012: Options for support to agriculture and food security under climate change. *Environmental Science & Policy*, **15**, 136-144.

Visser, M.E., 2008: Keeping up with a warming world: assessing the rate of adaptation to climate change. *Proceedings of the Royal Society B*, **275(1635)**, 649-659.

Voinov, A. and H. Cardwell, 2009: The energy-water nexus: why should we care? *Journal of Contemporary Water Research & Education*, **143**, 17-29.

Wade, S.D., J. Rance, and N. Reynard, 2013: The UK climate change risk assessment 2012: assessing the impacts on water resources to inform policy makers. *Water Resources Management*, **27(4)**, 1085-1109.

Wang, C., T. He, and F. Chen, 2013: Evolutionary thinking in restoration under global environmental changes. *Journal of Plant Ecology*, doi:10.1093/jpe/rtt005.

Ward, P.J., W.P. Pauw, M.W. Van Buuren, and M.A. Marfai, 2013: Governance of flood risk management in a time of climate change: the cases of Jakarta and Rotterdam. *Environmental Politics*, **22(3)**, 518-536.

Warner, K., M. Hamza, A. Oliver-Smith, F. Renaud, and A. Julca, 2010: Climate change, environmental degradation and migration. *Natural Hazards*, **55(3)**, 689-715.

Washington-Allen, R.A., D.D. Briske, H.H. Shugart, and L.F. Salo, 2010: Introduction to special feature on catastrophic thresholds, perspectives, definitions, and applications. *Ecology and Society*, **15(3)**, 38, www.ecologyandsociety.org/vol15/iss3/art38/.

Watkiss, P., 2011: Aggregate economic measures of climate change damages: explaining the differences and implications. *Wiley Interdisciplinary Reviews: Climate Change*, **2(3)**, 356-372.

Webb, R. and J. Beh, 2013: *Leading Adaptation Practices and Support Strategies for Australia: An International and Australian Review of Products and Tools*. National Climate Change Adaptation Research Facility (NCCARF), Griffith University, Gold Coast Campus, Southport, Australia, 106 pp.

Weber, E.U., 2006: Experience-based and description-based long term learning: why global warming doesn't scare us (yet). *Climatic Change*, **77**, 103-120.

Webster, M., A.P. Sokolov, J.M. Reilly, C.E. Forest, S. Paltsev, A. Schlosser, C. Wang, D. Kicklighter, M. Sarofim, and H.D. Jacoby, 2012: Analysis of climate policy targets under uncertainty. *Climatic Change*, **112(3-4)**, 569-583.

Weichselgartner, J. and E. Breviere, 2011: The 2002 flood disaster in the Elbe region, Germany: a lack of context-sensitive knowledge. In: *Dynamics of Disaster: Lessons on Risk, Response, and Recovery* [Dowty, R.A. and B.L. Allen (eds.)]. Earthscan, London, UK, pp. 141-158.

Weitzman, M.L., 2009: On modeling and interpreting the economics of catastrophic climate change. *The Review of Economics and Statistics*, **91(1)**, 1-19.

Wenkel, K.-O., M. Berg, W. Mirschel, R. Wieland, C. Nendel, and B. Köstner, 2013: LandCaRe DSS – an interactive decision support system for climate change impact assessment and the analysis of potential agricultural land use adaptation strategies. *Journal of Environmental Management*, **27(Suppl.)**, S168-S183.

Wenzel, G., 2004: From TEK to IQ: Inuit Qaujimajatuqangit and Inuit cultural ecology. *Arctic Anthropology*, **41(2)**, 238-250.

West, J.M., S.H. Julius, P. Kareiva, C. Enquist, J.J. Lawler, B. Petersen, A.E. Johnson, and M.R. Shaw, 2009: U.S. natural resources and climate change: concepts and approaches for management adaptation. *Environmental Management*, **44**, 1001-1021.

Westerhoff, L., E.C.H. Keskitalo, H. McKay, J. Wolf, D. Ellison, I. Botetzagias, and B. Reysset, 2010: Planned adaptation measures in industrialised countries: a comparison of select countries within and outside the EU. In: *Developing Adaptation Policy and Practice in Europe: Multi-level Governance of Climate Change* [Keskitalo, E.C.H. (ed.)]. Springer, Dordrecht, Netherlands, pp. 271-338.

Westerhoff, L., E.C.H. Keskitalo, and S. Juhola, 2011: Capacities across scales: local to national adaptation policy in four European countries. *Climate Policy*, **11(4)**, 1071-1085.

Wheeler, S.M., 2012: Spatial planning and climate change. *Housing Studies*, **27(1)**, 157-158.

Whitmarsh, L., 2011: Scepticism and uncertainty about climate change: dimensions, determinants and change over time. *Global Environmental Change*, **21(2)**, 690-700.

Wilbanks, T.J. and R.W. Kates, 2010: Beyond adapting to climate change: embedding adaptation in responses to multiple threats and stresses. *Annals of the Association of American Geographers*, **100(4)**, 719-728.

Wilby, R.L. and S. Dessai, 2010: Robust adaptation to climate change. *Weather*, **65(7)**, 180-185.

Wilby, R.L. and R. Keenan, 2012: Adapting to flood risk under climate change. *Progress in Physical Geography*, **36(3)**, 348-378.

WMO, 2011: *Climate Knowledge for Action: A Global Framework for Climate Services – Empowering the Most Vulnerable*. The Report of the High Level Taskforce for the Global Framework for Climate Services, World Meteorological Organization (WMO), Geneva, Switzerland, 240 pp.

Wodon, Q. and H. Zaman, 2010: Higher food prices in Sub-Saharan Africa: poverty impact and policy responses. *The World Bank Research Observer*, **25(1)**, 157-176.

Wolf, J. and S.C. Moser, 2011: Individual understandings, perceptions, and engagement with climate change: insights from in-depth studies across the world. *Wiley Interdisciplinary Reviews: Climate Change*, **2(4)**, 547-569.

Wolf, J., I. Lorenzoni, R. Few, V. Abrahamson, and R. Raine, 2009: Conceptual and practical barriers to adaptation: vulnerability and responses to heat waves in the UK. In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, N.W., I. Lorenzoni, and K. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK, pp. 181-196.

Wolf, J., W.N. Adger, I. Lorenzoni, V. Abrahamson, and R. Raine, 2010: Social capital, individual responses to heat waves and climate change adaptation: an empirical study of two UK cities. *Global Environmental Change*, **20(1)**, 44-52.

Wolf, J., I. Allice, and T. Bell, 2013: Values, climate change, and implications for adaptation: evidence from two communities in Labrador, Canada. *Global Environmental Change*, **23(2)**, 548-562.

Wookey, P.A., R. Aerts, R.D. Bardgett, F. Baptist, K.A. Bråthen, J.H.C. Cornelissen, L. Gough, I.P. Hartley, D.W. Hopkins, S. Lavorel, and G.R. Shaver, 2009: Ecosystem feedbacks and cascade processes: understanding their role in the responses of Arctic and alpine ecosystems to environmental change. *Global Change Biology*, **15(5)**, 1153-1172.

Yang, W., N.H. Wong, and G. Zhang, 2012: A comparative analysis of human thermal conditions in outdoor urban spaces in the summer season in Singapore and Changsha, China. *International Journal of Biometeorology*, **57**, 895-907.

Yates, C.J., A. McNeill, J. Elith, and G.F. Midgley, 2010: Assessing the impacts of climate change and land transformation on Banksia in the South West Australian Floristic Region. *Diversity and Distributions*, **16(1)**, 187-201.

Young, O., 2006: Vertical interplay among scale-dependent environmental and resource regimes. *Ecology and Society*, **11(1)**, 27, www.ecologyandsociety.org/vol11/iss1/art27/.

Zelazowski, P., Y. Malhi, C. Huntingford, S. Sitch, and J.B. Fisher, 2011: Changes in the potential distribution of humid tropical forests on a warmer planet. *Philosophical Transactions of the Royal Society A*, **369(1934)**, 137-160.

Zhang, D.D., H.F. Lee, C. Wang, B.S. Li, Q. Pei, J. Zhang, and Y.L. An, 2011: The causality analysis of climate change and large-scale human crisis. *Proceedings of the National Academy of Sciences of the United States of America*, **108(42)**, 17296-17301.

Zhou, Q., P.S. Mikkelsen, K. Halsnæs, and K. Arnbjerg-Nielsen, 2012: Framework for economic pluvial flood risk assessment considering climate change effects and adaptation benefits. *Journal of Hydrology*, **414**, 539-549.

Zhu, X., M.M. Linham, and R.J. Nicholls, 2010: *Technologies for Climate Change Adaptation-Coastal Erosion and Flooding*. UNEP Risø Centre on Energy, Climate and Sustainable Development, Roskilde, Denmark, 150 pp.

Ziervogel, G., P. Johnston, M. Matthew, and P. Mukheibir, 2010a: Using climate information for supporting climate change adaptation in water resource management in South Africa. *Climatic Change*, **103(3-4)**, 537-554.

Ziervogel, G., M. Shale, and M. Du, 2010b: Climate change adaptation in a developing country context: the case of urban water supply in Cape Town. *Climate and Development*, **2**, 94-110.

Zinn, M.D., 2007: Adapting to climate change: environmental law in a warmer world. *Ecology Law Quarterly*, **34(1)**, 61-105.

Ziska, L.H., D.M. Blumenthal, G.B. Runion, E.R. Hunt Jr., and H. Diaz-Soltero, 2011: Invasive species and climate change: an agronomic perspective. *Climatic Change*, **105(1-2)**, 13-42.

17

Economics of Adaptation

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This chapter should be cited as:
Chambwera, M., G. Heal, C. Dubeux, S. Hallegatte, L. Leclerc, A. Markandya, B.A. McCarl, R. Mechler, and J.E. Neumann, 2014: Economics of adaptation. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 945-977.

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Frequently Asked Questions

17.1: Given the significant uncertainty about the effects of adaptation measures, can economics contribute much to decision making in this area? 954

17.2: Could economic approaches bias adaptation policy and decisions against the interests of the poor, vulnerable populations, or ecosystems? 961

17.3: In what ways can economic instruments facilitate adaptation to climate change in developed and developing countries? 965

Executive Summary

In the presence of limited resources and a range of objectives, adaptation strategy choices involve trade-offs among multiple policy goals (*high confidence*). The alternative policy goals include development and climate change mitigation. Economics offers valuable insights into these trade-offs and into the wider consequences of adaptation. It also helps to explain the differences between the potential of adaptation and its achievement as a function of costs, barriers, behavioral biases, and resources available. {17.2.7.1-2, 17.3.1}

Economic thinking on adaptation has evolved from a focus on cost-benefit analysis and identification of "best economic" adaptations to the development of multi-metric evaluations including the risk and uncertainty dimensions in order to provide support to decision makers (*high confidence*). Economic analysis is moving away from a unique emphasis on efficiency, market solutions, and cost-benefit analysis of adaptation to include consideration of non-monetary and non-market measures, risks, inequities and behavioral biases, and barriers and limits and consideration of ancillary benefits and costs. One role of economics is to contribute information to decision makers on the benefits and costs, including a number of non-monetary items, and on the equity impacts of alternative actions. It does not provide a final ranking for policy makers. A narrow focus on quantifiable costs and benefits can bias decisions against the poor and against ecosystems and those in the future whose values can be excluded or are understated. Sufficiently broad-based approaches, however, can help avoid such maladaptation. Indeed the evidence shows that maladaptation is a possibility if the evaluation approaches taken are not comprehensive enough in this sense. {17.2.3, 17.3.2}

The theoretical basis for economic evaluation of adaptation options is clear, and can be and has been applied to support decisions in practical contexts (*medium confidence*). There is extensive experience of applying the concepts and methods underlying the economic framework in non-adaptation contexts, which is useful for designing climate adaptation policies. The limited empirical evidence available shows a number of cases where desirable adaptation strategies have been identified based on these economic tools. The findings show that adaptation is highly regional and context specific. Thus the results do not readily permit widespread generalizations about the nature of attractive adaptation actions. {17.2, 17.4.1-2, 17.4.4}

Both private and public sectors have a role to play in the development and implementation of adaptation measures (*high confidence*). Economic theory and empirical results show that a degree of adaptation will be autonomously carried out by private parties in response to climate change. However, the private sector alone will often not provide the desirable level of adaptation with some types of actions not undertaken due to costs, incentives, nature of beneficiaries, and resource requirements. This implies the public sector will need to play a strong role. There are also other reasons for public action such as overcoming barriers, developing technologies, representing current and future equity concerns, and other items. {17.2.1, 17.3.1}

The theory and the evidence indicate that adaptation cannot generally overcome all climate change effects (*high confidence*). In addition to there being biophysical limits to adaptation, such as the inability to restore outdoor comfort under high temperatures, some adaptation options will simply be too costly or resource intensive or will be cost ineffective until climate change effects grow to merit investment costs. Thus the desirability of adaptation options will vary with time and climate change realization. {17.2.2, 17.2.5}

Adaptation generally needs to be seen in the frame of the overall development path of the country, particularly for developing countries (*high confidence*). Development and adaptation can be complementary or competitive. Also development can yield positive ancillary adaptation effects or co-benefits, provided it takes into account climate change in its design. Adaptation actions can provide significant co-benefits such as alleviating poverty or enhancing development. Many aspects of economic development also facilitate adaptation to a changing climate, such as better education and health, and there are adaptation strategies that can yield welfare benefits even in the event of a constant climate, such as more efficient use of water and more robust crop varieties. Maximizing these synergies requires a close integration of adaptation actions with existing policies, referred to as "mainstreaming." {17.2.7, 17.2.3.1-2}

Not all adaptation actions are investment-based. Policy actions are also important tools for adaptation (*medium confidence*). These include direct research & development (R&D) funding, environmental regulation, economic instruments, and education. Economic instruments have high potential as flexible tools because they directly and indirectly provide incentives for anticipating and reducing impacts and can have lower costs in the public budget. These instruments are currently not well explored in an adaptation context apart from risk

financing instruments. Existing incentives will lead to a set of private adaptation actions. They include risk sharing and transfer mechanisms (insurance), loans, public-private finance partnerships, payment for environmental services, improved resource pricing (water markets), charges and subsidies including taxes, norms and regulations, and behavioral modification approaches. These instruments offer some useful possibilities for addressing climate change but they also have problems of effective implementation that need to be addressed. The problems can be particularly severe in developing countries. {17.4-5}

Risk financing mechanisms at local, national, regional, and global scales contribute to increasing resilience to climate extremes and climate variability, but involve major design challenges so as to avoid providing disincentives, causing market failure and worsening equity situations (*medium confidence*). Mechanisms include insurance; reinsurance; micro insurance; and national, regional, and global risk pools. The public sector often plays a key role as regulator, provider, or insurer of last resort. Risk financing can directly promote adaptation through providing claim payments after an event and allow for improved decisions under risk pre-event (strong evidence). It can also directly provide incentives for reducing risk, yet the evidence is weak and the presence of many counteracting factors often leads to disincentives, which is known as moral hazard. {17.5.1}

Limited evidence indicates a gap between global adaptation needs and the funds available for adaptation (*medium confidence*). There is a need for a better assessment of global adaptation costs, funding, and investment. Studies estimating the global costs of adaptation are characterized by shortcomings in data, methods, and coverage (*high confidence*). {14.2, 17.4; Tables 17-2, 17-3}

Economics offers a range of techniques appropriate for conducting analysis in the face of uncertainties, and the choice of the most appropriate technique depends on the nature of the problem and the nature and level of uncertainty (*high confidence*). Uncertainty is unavoidable in analyses of adaptation to climate change because of lack of data, the efficacy of adaptation actions, and uncertainties inherent in forecasting climate change. Approximate approaches are often necessary. There is a strong case for the use of economic decision making under uncertainty, working with tools such as cost-benefit and related approaches that include time dimensions (real options techniques), multi-metrics approaches, and non-probabilistic methodologies. There are methodologies that are able to capture non-monetary effects and distributional impacts, and to reflect ethical considerations. {17.3.2.1-3}

Selected regional and sectoral studies suggest some core considerations and characteristics that should be included in the economic analyses of adaptation (*medium confidence*). These desirable characteristics include a broad representation of relevant climate stressors to ensure robust economic evaluation; consideration of multiple alternatives and/or conditional groupings of adaptation options; rigorous economic analysis of costs and benefits across the broadest possible market and non-market scope; and a strong focus on support of practical decision making that incorporates consideration of sources of uncertainty. Few current studies manage to include all of these considerations. {17.4.3}

17.1. Background

This chapter assesses the literature on the economics of climate change adaptation, building on the Fourth Assessment Report (AR4) and the increasing role that economic considerations are playing in adaptation decision making and policy. AR4 provided a limited assessment of the costs and benefits of adaptation, based on narrow and fragmented sectoral and regional literature (Adger et al., 2007). Substantial advances have been made in the economics of climate change adaptation after AR4.

The specific objectives involved in an adaptation effort can be diverse. One may try to cancel all impacts (negative and positive), maintaining the status quo. Alternatively one can try to cancel adverse impacts and capture positive opportunities, so that the welfare gain (or loss) is maximized (or minimized).

Part of the literature presents adaptation as a continuous, flexible process, based on learning and adjustments (see, e.g., IPCC, 2012). Adaptation projects informed by this approach emphasize learning and experimenting, plus the value of using reversible and adjustable strategies (Berkhout et al., 2006; McGray et al., 2007; Pelling et al., 2007; Leary et al., 2008; Hallegatte, 2009; Hallegatte et al., 2011c).

Adaptation action and policy has also advanced since AR4, and the literature on the economics of adaptation has reflected this. This chapter builds on other chapters in this assessment—in particular Chapter 2, which sets the basis for decision making, recognizing economics as a decision support tool for both public and private actors. The type of economic approach used depends on factors discussed in Chapter 2, among others, including the agent making the decision, the nature or type of decision, the information used to make the decision, who implements the decision, others affected by the outcomes, and the values attached to those outcomes. While realizing the linkages between adaptation and mitigation, the starting point of this chapter is that adaptation is a given need.

This chapter assesses the scientific literature covering the economic aspects of adaptation; decision making and the economic context of adaptation, including economic barriers to adaptation decision making, and uncertainty; costing adaptation; and the economic and related instruments to provide incentives for adaptation.

17.2. Economic Aspects of Adaptation

When considering adaptation, economic studies give insight into issues regarding the roles of various actors in society, the character of adaptation strategies, the types of benefits and costs involved, the role of time, and a number of other factors that we discuss in this section.

17.2.1. Public and Private Actors in Adaptation Implementation

Previous IPCC reports—i.e., the Third Assessment Report (TAR) and First Assessment Report (FAR)—indicate adaptation actions can be autonomous, planned, or natural. Autonomous actions are undertaken mostly by private parties while planned can be undertaken by private or public actors. Natural adaptation is that occurring within the ecosystem in reaction to climate change but may be subject to human intervention (see discussion in Section 14.1).

In terms of human actions there are important economic distinctions regarding the roles of private and public actors. Some adaptation actions create public goods that benefit many and in such cases the implementing party cannot typically capture all the gains. For example, if an individual pays to protect a coastline or develop an improved irrigation system, the gains generally go to many others. Classical economic theory (Samuelson, 1954) and experience plus observations regarding adaptation (Mendelsohn, 2000; Osberghaus et al., 2010a; Wing and Fisher-Vanden, 2013) indicate that such actions will not receive appropriate levels of private investment (creating a market failure). In turn, this calls for public action by elements of broader society (e.g., governments, non-governmental organizations (NGOs), or international organizations).

Other reasons for public provision or public regulation of certain adaptation measures that lead to less than a socially desirable level of adaptation are discussed in Section 17.3.

17.2.2. Broad Categorization of Adaptation Strategies

There are many possible adaptation measures, as indicated in the TAR and FAR, plus Chapters 14 and 15. In economic terms these include a mixture of public and private actions taken in both domestic and international settings. A broad characterization of these and who might undertake them follows:

- Altered patterns of enterprise management, facility investment, enterprise choice, or resource use (mainly private)
- Direct capital investments in public infrastructure (e.g., dams and water management—mainly public)
- Technology development through research (e.g., development of crop varieties—private and public)
- Creation and dissemination of adaptation information (through extension or other communication vehicles—mainly public)
- Human capital enhancement (e.g., investment in education—private and public)
- Redesign or development of adaptation institutions (e.g., altered forms of insurance—private and public)
- Changes in norms and regulations to facilitate autonomous actions (e.g., altered building codes, technical standards, regulation of grids/networks/utilities, environmental regulations—mainly public)
- Changes in individual behavior (private, with possible public incentives)
- Emergency response procedures and crisis management (mainly public).

Not all adaptation involves investment or is costly. Some adaptation measures involve modification of recurring expenditures as opposed to new investments (replacing depreciated equipment with more adapted items). Sometimes adaptation involves changes in behaviors and lifestyles (e.g., due to increased frequency of heat waves).

17.2.3. Broad Definition of Benefits and Costs

The consequences of adaptation decisions cannot be expressed comprehensively through standard economic accounting of costs and revenues. Adaptation decisions can also affect other items such as income distribution and poverty (Jacoby et al., 2011); the regional distribution of economic activity, including employment; non-market factors such as water quality, ecosystem function, and human health; and social organization and cultural practices.

Adaptation choices have broad ranging and complex impacts on such issues as:

- Macroeconomic performance (see, e.g., Fankhauser and Tol, 1995)
- Allocation of funds with a crowding out effect on other climate and non-climate investments with consequences for future economic growth (Hallegatte et al., 2007; Hallegatte and Dumas, 2008; Wang and McCarl, 2013)
- Welfare of current and future generations through resource availability and other non-monetary effects
- Risk distributions on all of the above due to routine variability plus uncertain estimates of the extent of climate change and adaptation benefits and costs.

A number of these items pose challenges for measurement and certainly for monetization. Generally this implies that any analysis be multi-metric, with part in monetary terms and other parts not, and some in precise quantitative terms and others not (for more discussion see Section 17.3). In view of this, it is reasonable to conclude that an unbiased, comprehensive analysis would consist of a multi-metric analysis encompassing cost-benefit and other monetary items plus non-monetary measures. That analysis would support adaptation decision making.

17.2.3.1. Ancillary Economic Effect of Adaptation Measures and Policies

In addition to creating an economy that is more resilient to the effects of climate change, adaptation strategies often have ancillary effects of substantial importance. These can be positive (co-benefits) or negative (co-costs). Ancillary effects also arise when actions aimed primarily at mitigation or non-climate-related matters alter climate adaptation. Examples include:

- Sea walls that protect against sea level rise and at the same time protect against tsunamis. However, they can have co-costs causing damages to adjacent regions, fisheries, and mangroves (Frihy, 2001).
- Crop varieties that are adapted to climate change have enhanced resistance to droughts and heat and so also raise productivity in non-climate change-related droughts and temperature extreme (Birthal et al., 2011).
- Better building insulation that mitigates energy use and associated greenhouse gas emissions also improves adaptation by protecting against heat (Sartori and Hestnes, 2007).
- Public health measures that adapt to increases in insect-borne diseases also have health benefits not related to those diseases (Egbendewe-Mondzozo et al., 2011).
- More efficient use of water—adaptation to a drier world—will also yield benefits under current conditions of water scarcity. Development of improved desalination methods has the same merits (Khan et al., 2009).
- Locating infrastructure away from low-lying coastal areas provides adaption to sea level rise and will also protect against tsunamis.
- Reducing the need to use coal-fired power plants through energy conserving adaptation will also provide mitigation, improve air quality, and reduce health impacts (Burtraw et al., 2003).

17.2.3.2. Economic Consideration of Ancillary Effects

Many studies argue that co-benefits should be factored into decision making (e.g., Brouwer and van Ek, 2004; Ebi and Burton, 2008; Qin et al., 2008; de Bruin et al., 2009a; Kubal et al., 2009; Viguie and Hallegatte, 2012). If a country has a fixed sum of money to allocate between two competing adaptation projects, and both strategies generate net positive ancillary effects, then the socially optimal allocation of adaptation investment will differ from the private optimum and will favor the activity with the larger direct plus ancillary effects.

17.2.4. Adaptation as a Dynamic Issue

Adaptation is not a static concern. Rather it evolves over time in response to a changing climate (Hallegatte, 2009). Adaptation is perhaps best handled via a long-term transitional, continuous, flexible process that involves learning and adjustment (Berkhout et al., 2006; McGray et al., 2007; Pelling et al., 2007; Leary et al., 2008; Hallegatte, 2009; Hallegatte et al., 2011c; IPCC, 2012). Generally the literature indicates that optimal adaptation and the desirability of particular strategies will vary over time depending on climate forcing plus other factors such as technology availability and its maturity (de Bruin et al., 2009b). In the next few decades, during which time projected temperatures do not vary substantially across socioeconomic/climate scenarios, adaptation is the main economic option for dealing with realized climate change. Risk is also an important aspect, with the longer term being more uncertain that the near term. Risk-sensitive decisions often include the options of acting or of waiting (Linquiti and Vonortas, 2012). The issue of options is discussed further in Beltratti et al. (1998), which covers uncertainty about future preferences through option values.

Dynamics also are involved with strategy persistence owing to the decadal to century time scale implications of some adaptation strategies such as construction of seawalls or discovery of drought-resistant crop genes. The desirability of investments with upfront costs and persistent benefits increases when the benefits are long lasting or when climate change damages accumulate slowly (Agrawala et al., 2011; de Bruin, 2011; Wang and McCarl, 2013). However, maladaptation effects rising over time are also possible as protecting now can expand investment in vulnerable areas and worsen future vulnerability (Hallegatte, 2011).

17.2.5. Practical Adaptation Strategy Attractiveness and Feasibility

Adaptation cannot reasonably overcome all climate change effects (Parry et al., 2009). A number of factors will limit strategy adoption and



Figure 17-1 | The narrowing of adaptation from the space of all possible adaptations to what will be done. Forces causing the narrowing are listed in black.

preclude elimination of all climate change effects. A conceptual way of looking at this for a given adaptation endeavor is in Figure 17-1. The first outside circle represents the "adaptation needs," that is, the set of adaptation actions that would be required to avoid any negative effect (and capture all positive effects) from climate change. It can be reduced by climate change mitigation, that is, by limiting the magnitude of climate change. The second circle represents the subset of adaptation actions that are possible considering technical and physical limits. Improving what can be done, for instance, through research and development, can expand this circle. The area between the first and second circles is the area of "unavoidable impacts" that one cannot adapt to (for instance, it is impossible to restore outdoor comfort under high temperature). The third circle represents the subset of adaptation actions that are desirable considering limited resources and competing priorities: some adaptation actions will be technically possible, but undesirable because they are too expensive and there are better alternative ways of improving welfare (e.g., investing in health or education). This circle can be expanded through economic growth, which increases resources that can be dedicated to adaptation. Finally, the last circle represents what will be done, taking into account the fact that market failures or practical, political, or institutional constraints will make it impossible to implement some desirable actions (see Chapter 15 and Section 17.3). The area between the first and the last circles represents residual impacts (i.e., the impacts that will remain after adaptation, because adapting to them is impossible, too expensive, or impossible owing to some barriers).

This discussion has consequences for timing of adaptation financing, given continuous changes in climate over time and uncertainties in the resulting impacts. Mathew et al. (2012) recommend the use of soft, short-term and reversible adaptation options with co-benefits for local governments. Giordano (2012) recommends the use of adaptive policies for modifying infrastructure, which can be robust across a wide range of plausible futures under climate change. Hochrainer and Mechler (2011) suggest that tools such as risk pooling may be more cost effective than risk reduction through engineering methods for low-frequency but high-impact hazards.

Financing adaptation programs is further discussed in the literature through the lens of distribution of costs. Stern (2006) argues climate change is characterized by a "double inequity," with those countries that are most vulnerable having generally contributed least (on a per capita basis) to the climate change drivers (Panayotou et al., 2002; Tol et al., 2004; Mendelsohn et al., 2006; Patz et al., 2007; SEGCC, 2007; Srinivasan et al., 2008; Füssel, 2010).

Distribution of responsibilities for financing adaptation has been the subject of lively debate. Füssel et al. (2012) note that answering the following questions can inform the debate on such burden sharing issues:

- Who pays for adaptation and how much should they contribute into the adaptation fund, and what criteria are appropriate in determining this?
- Who is eligible for receiving payments from the fund, and which criteria could be used for prioritizing recipients and for allocating funds?
- Which adaptation measures are eligible for funding, and what are the conditions and modalities for payment?
- How and by whom are such decisions made?

As of now no definitive conclusions have been reached. Table 17-1 sets out different approaches to defining eligibility for receiving adaptation funds.

17.2.6. Adaptation Benefits and Costs, Residual Damage, and Projects

Adaptation benefits are the reduction in damages plus any gains in climate-related welfare that occur following an adaptation action (National Research Council, 2010; World Bank, 2010a). Simplistically described, the cost of adaptation is the cost of any additional investment needed to adapt to or exploit future climate change (UNFCCC, 2007). But a full accounting needs to consider the resources spent to develop,

Table 17-1 | Four definitions of eligible adaptation.

Motivation for action	Relevant climatic factors	
	Observed and/or projected climate change	Climate change as well as natural climate variability
Climate is the main reason	*Definition 1*: Action occurs mainly to reduce the risks of observed or projected climate change. *Example*: Raising of existing dykes.	*Definition 2*: Action occurs mainly to reduce risks of climate change and climate variability. *Example*: Building of new dykes in areas that are currently unprotected.
Climate is one of several reasons	*Definition 3*: Actions that reduce the risks of observed or projected climate change even if they are also justified in the absence of climate change. *Example*: Economic diversification in predominantly agricultural regions.	*Definition 4*: Actions that reduce the risks of climate change and climate variability even if they are also justified in the absence of climate change. *Example*: Improved public health services.

Source: Füssel et al. (2012), adapted from Hallegatte (2008).

implement, and maintain the adaptation action along with accruing reduced damages or welfare increases involving monetary and non-monetary metrics.

Figure 17-2 provides a graphical representation of the link between the cost of adaptation (on the x-axis) and the residual cost of climate change (on the y-axis). A fraction of climate change damage can be reduced at no cost (e.g., by changing sowing dates in the agricultural sector). With increasing adaptation cost, climate change costs can be reduced further. In some cases (left-hand panel), sufficiently high adaptation spending can take residual cost to zero. In other cases (right-hand panel), some residual cost of climate change is unavoidable. Economics tells that the optimal level of adaptation equalizes the marginal adaptation cost and the marginal adaptation benefit, given by the point on the adaptation curves where the slope is –45°. If barriers and constraints (see Section 17.3) impose a suboptimal situation, the marginal costs and benefits of adaptation are not equal, possibly because there is too much investment in adaptation, so that investing $1 in adaptation reduces climate change residual cost by less than $1, or because there is not enough investment in adaptation and investing $1 more in adaptation would reduce residual cost by more than $1 (the situation in the right-hand panel).

Defining the costs and benefits of an "adaptation project" raises conceptual issues. Many actions have an influence on the impact of climate change without being adaptation projects per se (e.g., enhanced building norms). Many "adaptation projects" have consequences beyond a reduction in climate change impacts or an increase in welfare from exploiting opportunities (as discussed in the ancillary impacts section). Defining the adaptation component requires the definition of a baseline (What would be the impact of climate change in the absence of the adaptation action? What alternative projects would be implemented in the absence of climate change?), and the definition of "additionality"—the amount of additional loss reduction or welfare gain that happens because of the project. For instance, the building of new infrastructure may be marginally more costly because of adaptation to climate change but would still be undertaken without climate change and thus only a fraction of that cost and the resultant benefits would be labeled as occurring because of adaptation (see Dessai and Hulme, 2007).

In the climate change context, residual damages are those damages that remain after adaptation actions are taken. De Bruin et al. (2009b) and Hof et al. (2009) have examined the relationship between increasing adaptation effort and diminished residual damages.

17.2.7. A Broader Setting for Adaptation

Adaptation can be complementary to mitigation and to non-climate policies. An important concern is determining the balance between spending on adaptation versus that on other investments—mitigation and non-climate endeavors. Economics indicates the marginal social returns to all forms of expenditure should be the same, allowing for distributional impacts which can be done by differential weightings of benefits and costs to alternative income groups (Musgrave and Musgrave, 1973; Brent, 1996).

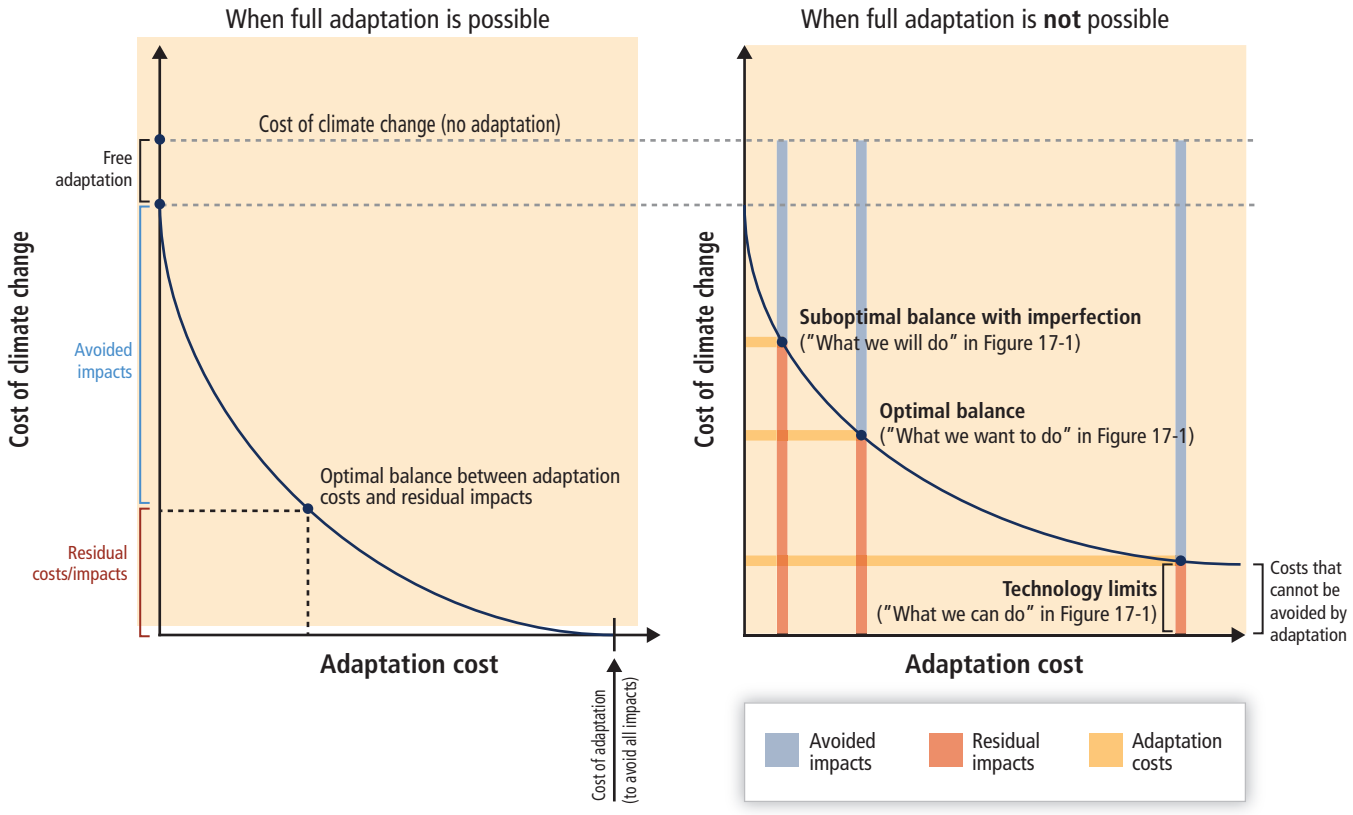

Figure 17-2 | Graphical representation of link between the cost of adaptation (on the x-axis) and the residual cost of climate change (on the y-axis). The left panel represents a case where full adaptation is possible, while the right panel represents a case in which there are unavoidable residual costs.

17.2.7.1. Adaptation and Mitigation as Competitive or Complementary Investments

Adaptation and mitigation funding require coordination as they are competing uses for scarce resources (WGII AR4 Chapter 18; Gawel et al., 2012). They also compete with consumption and non-climate investments. For example, some adaptation strategies use land (a shift from crops to livestock), as does mitigation via afforestation or biofuels, and all three would reduce ongoing crop production. Nevertheless, considering both adaptation and mitigation widens the set of actions and lowers the total cost of climate change (de Bruin et al., 2009a; Koetse and Rietveld, 2012; Wang and McCarl, 2013).

17.2.7.2. Adaptation and Development

There is a relationship between adaptation and socioeconomic development, particularly in lower income countries (as extensively discussed in Chapters 10, 13, and 20). In terms of complementarity between the two, studies show that both development and adaptation can be enhanced via climate-resilient road development (World Bank, 2009); installation of agricultural investments that enhance income, heat tolerance, and drought resilience (Butt et al., 2006;Ringer et al., 2008); or improvements in public health infrastructure that increase capability to deal with climate-enhanced disease and other diseases (Markandya and Chiabai, 2009; Samet, 2010). In addition, development in general can increase adaptive capacity through enhancements in human and other capital (Schelling, 1992, 1997; Tol, 2005; IPCC, 2012). Finally, adaptation efforts may reduce adaptation deficits regarding vulnerability to existing climate and enhance general development (Burton, 2004). Thus, development goals can be generally consistent with adaptation goals, with one possibly being an ancillary effect of the other, although this is not always the case. For example, Hansone et al. (2001) find that urbanization of flood-prone areas increases vulnerability and adaptation needs while Burby et al. (2001) and Hallegatte (2012) indicate better protection may trigger additional development in at-risk areas and create increased vulnerability to extreme events.

17.3. Decision Making and Economic Context for Adaptation

Adaptation will be carried out by multiple public and private actors who face a number of decision-making barriers that may limit adaptation. Chapter 16 and many papers (e.g., Fankhauser et al., 1999; Cimato and Mullan, 2010; Moser and Eckstrom 2010; Biesbroek et al., 2011; Fankhauser and Soare, 2013) investigate these barriers. This section

Frequently Asked Questions

FAQ 17.1 | Given the significant uncertainty about the effects of adaptation measures, can economics contribute much to decision making in this area?

Economic methods have been developed to inform a wide range of issues that involve decision making in the face of uncertainty. Indeed some of these methods have already been applied to the evaluation of adaptation measures, such as decisions on which coastal areas to protect and how much to protect them.

A range of methods can be applied, depending on the available information and the questions being asked. Where probabilities can be attached to different outcomes that may result from an adaptation measure, economic tools such as risk and portfolio theory allow us to choose the adaptation option that maximizes the expected net benefits, while allowing for the risks associated with different options. Such an approach compares not only the net benefits of each measure but also the risks associated with it (e.g., the possibility of a very poor outcome).

In situations where probabilities cannot be defined, economic analysis can define scenarios that describe a possible set of outcomes for each adaptation measure that meet some criteria of minimum acceptable benefits across a range of scenarios, allowing the decision maker to explore different levels of acceptable benefits in a systematic way. That, of course, hinges on the definition of "acceptability," which is a complex matter that accounts for community values as well as physical outcomes. These approaches can be applied to climate change impacts such as sea level rise, river flooding, and energy planning.

In some cases it is difficult to place specific economic values on important outcomes (e.g., disasters involving large-scale loss of life). An alternative to the risk or portfolio theory approach can then be used, that identifies the least-cost solution that keeps probable losses to an acceptable level.

There are, however, still unanswered questions on how to apply economic methods to this kind of problem (particularly when the changes caused by climate change are large and when people's valuations may be changed), and on how to improve the quality of information on the possible impacts and benefits.

reviews them from an economic perspective, and then turns to the decision-making frameworks that can help implement adaptation actions in spite of these barriers.

17.3.1. Economic Barriers to Adaptation Decision Making

17.3.1.1. Transaction Costs, Information, and Adjustment Costs

Transaction costs include the costs of accessing markets and information, along with reaching an agreement and enforcement costs (Coase, 1937, 1960; Williamson, 1979). Because of transaction costs, a beneficial adaptation action may be undesirable. Two specific types of transaction costs are those relating to information and those relating to adjustment.

Information acquisition costs can represent a significant obstacle, for instance, when climate and weather data are costly or difficult to access (e.g., Cimato and Mullan, 2010; Ford et al., 2011; Scott et al., 2011). Because information is a public good, private actors tend to under-provide it and there is a role for government and public authorities to support its production and dissemination (e.g., through research funding, observation networks, or information distribution systems; Fankhauser et al., 1999; Mendelsohn, 2000; Trenberth, 2008).

Adjustment costs represent another barrier, especially in the presence of uncertainty and learning, and when long-lived capital is concerned. Fankhauser et al. (1999) discuss adjustment costs as a barrier to early capital replacement to adapt to a different climate. Kelly and Kolstad (2005) define adjustment costs as the cost incurred while learning about new climate conditions. Using these different definitions, these analyses suggest that adjustment costs can represent a significant share of adaptation costs.

17.3.1.2. Market Failures and Missing Markets

Adaptation may also face market failures such as externalities, information asymmetry, and moral hazards (see Section 17.2.1; Osberghaus et al., 2010a). As a consequence, some socially desirable actions may not be privately profitable. For example, flood mitigation measures may not be implemented in spite of their benefits, when flood risks are partly assumed by insurance or post-disaster support, transferring risk to the community (a case of moral hazard; Burby et al., 1991; Laffont, 1995). There are also externalities, as adaptation actions by one household, firm, or even country may create higher damages for others. This is the case with transboundary waters, when increased irrigation in one country creates water scarcity downstream (Goulden et al., 2009). Trans-sector effects can also take place, for instance when adaptation in one sector creates needs in another sector (e.g., the impact on transportation of agriculture adaptation; see Attavanich et al., 2013). Incentives for private adaptation actions may also be lacking for public goods and common resources without property rights (e.g., biodiversity and natural areas, tradition, and culture). And adaptation may exhibit increasing returns or large fixed costs, leading to insufficient adaptation investments (e.g., Eisenack, 2013). In such contexts, public norms and standards, direct public investment, tax measures, or national or international institutions for adaptation coordination are needed to avoid maladaptation.

17.3.1.3. Behavioral Obstacles to Adaptation

Economic agents adapt continuously to climate conditions, though not always using the available information, especially long-term projections of consequences (Camerer and Kunreuther, 1989; Thaler, 1999; Michel-Kerjan, 2006). Individuals often defer choosing between ambiguous choices (Tversky and Shafir, 1992; Trope and Lieberman, 2003) and make decisions that are time inconsistent (e.g., they attribute a lower weight to the long term through "hyperbolic discounting"; see Ainslie, 1975). They also systematically favor the status quo and familiar choices (Johnson and Goldstein, 2003). Also, individuals value profits and losses differently (Tversky and Kahnman, 1974). Behavioral issues may lead to suboptimal adaptation decisions, as illustrated with case studies in Germany and Zimbabwe in Grothmann and Patt (2005). Particularly important is the fact that the provision of climate information needs to account for cognitive failures (Suarez and Patt, 2004; Osberghaus et al., 2010b). Individual behavioral barriers extend to cultural factors and social norms, which can support or impair adaptation as illustrated by Nielsen and Reenberg (2010) in Burkina Faso.

17.3.1.4. Ethics and Distributional Issues

A difficulty in allocating adaptation resources noted in Section 17.2.3 is the limitation of indicators based on costs and benefits (Adger et al., 2005; Füssel, 2010). Outcomes are often measured using such methods but their limits are well known, (e.g., CMEPSP, 2009; OECD, 2009; Heal, 2012) and include the failure to take into account resource depletion, environmental change, and distributional issues.

Distributional issues may justify public intervention based on ethics and values. Climate change impacts vary greatly by social group, and many have suggested that the poor are particularly vulnerable (e.g., Stern, 2006; Füssel et al., 2012). Some individuals, firms, communities, and even countries may be unable to afford adaptation, even if it is in their own interest. Also, individuals with different world views or preferences (e.g., regarding risk aversion; see Adger et al., 2009) may ask for different adaptation measures and have different views of what is an acceptable level of residual risk (Peters and Slovic, 1996). Consideration of justice and fairness will play a role in adaptation option design (Adger et al., 2006; Brauch, 2009a,b; Dalby, 2009; O'Brien et al., 2009, 2010; Pelling and Dill, 2009). The implementation of adaptation options may thus require taking into account the political economy of reforms and the need to compensate losers (World Bank, 2012).

The traditional economic approach suggests choosing the most cost-effective projects and then resorting to financial transfers to satisfy equity objectives (Atkinson and Stiglitz, 1976; Brown and Heal, 1979). However, this embodies strong assumptions including the ability to realize perfect and costless financial transfers. In more realistic situations the choice is not so clear cut. In practical terms, transfers are difficult to organize and may not be politically acceptable (Kanbur, 2010).

In these cases, adaptation decision making needs to account for both the net benefits and the impacts on equity (Aakre and Rübbelke, 2010).

17.3.1.5 Coordination, Government Failures, and Political Economy

One of the main roles of governments and local authorities is to remove barriers—realigning the incentives of individuals with the goals of society, providing the public goods needed for adaptation, or helping with behavioral and cognitive biases. But governments and local authorities face their own barriers, often referred to as government or regulatory failures (Krueger, 1990). First, government and local authority decision makers, as individuals, face their own barriers, such a cognitive and behavioral biases (Podsakoff et al., 1990). Public decision makers are also confronted with moral hazard, for instance, when subnational entities are provided support from the government in case of disaster (Michel-Kerjan, 2006). Second, governments may have access to insufficient resources or limited adaptation capacity, especially in poorer countries and where governments have limited access to capital markets and are unable to fund projects, even when they are cost efficient (e.g., Brooks et al., 2005; Smit and Wandel, 2006; World Bank, 2012). There can also be coordination failures within the government, as many adaptation options require multi-ministry actions (e.g., the reduction of flood risks may require some prevention measure implemented by the environmental ministry and an insurance scheme regulated by the ministry of finance; World Bank, 2013).

Other government failures can arise. Frequently government action is driven by narrow interest groups and is not in the public interest (Levine and Forrence, 1990; James, 2000). Multi-stakeholder approaches have been shown to help address these problems, with a relevant example for this context being coral reef management in Tobago (Adger et al., 2005).

17.3.1.6. Uncertainty

Decisions about adaptation have to be made in the face of uncertainty on items ranging from demography and technology to economic futures. Climate change adds additional sources of uncertainty, including uncertainty about the extent and patterns of future climate change (see the WGI contribution to the AR5), which is dependent on uncertain socioeconomic development pathways and climate policies (see the WGIII contribution to the AR5), and uncertainty about the reaction and adaptation of ecosystems (see Chapters 3 to 13).

Patt and Schröter (2008) show in a case study in Mozambique that major uncertainties are a strong barrier to successful adaptation. Uncertainty, coupled with the long lifespan of a number of options, can lead to "maladaptation," that is, an adaptation action that leads to increased vulnerability. An "*avoidable*" maladaptation arises from a poor *ex ante choice*, where available information is not used properly. An "*unavoidable*" *ex post* maladaptation can result from entirely appropriate decisions based on the information that was the best available *at the time of decision making*, but subsequently proves to have been wrong. An example of the latter is a precautionary restriction prohibiting new construction in areas potentially at risk of sea level rise. Applying such a precautionary approach makes sense when (1) decisions are at least partly irreversible (e.g., building in flood-prone areas cannot easily be "un-built") and (2) the cost of a worst-case scenario is very high. Such a precautionary measure can make economic sense *ex ante*, even if sea level rise eventually remains in the lower range of possible outcomes, making the construction restriction unnecessary.

17.3.2. Economic Decision Making with Uncertainty

Decision making under uncertainty is a central question for climate change policy and is discussed in many chapters of the AR5, especially in Chapter 2 and WGIII AR5 Chapters 2 and 3. This section focuses on the economic approaches to decision making under uncertainty, including decision-making techniques, valuation tools, and multi-metric decision making.

17.3.2.1. Cost-Benefit Analysis and Related Methods

There are different tools for decision making that can be applied in different contexts and with different information. Cost-benefit analysis under uncertainty applied to adaptation uses subjective probabilities for different climate futures (e.g., Tebaldi et al., 2005; New and Hulme, 2006; see also Chapter 2). The "best" project is the one that maximizes the expected net present value of costs and benefits. Risk aversion can be taken into account through (nonlinear) welfare functions or the explicit introduction of a risk premium.

When conducting cost-benefit analyses under uncertainty, an important question is the timing of action, that is, the possibility of delaying a decision until more information is available (e.g., Fankhauser and Soare, 2013). Real option techniques are an extension of cost-benefit analysis to capture this possibility and balance the costs and benefits of delaying a decision (Arrow and Fisher, 1974; Henry, 1974). The benefits depend on how much learning can take place over time. A key issue concerns irreversible actions, such as the destruction of a unique environment (Heal and Kristrom, 2003).

Application of cost-benefit or real option analysis requires evaluations in monetary terms. For market impacts, prices may need to be corrected for policies, monopoly power, or other external factors distorting market prices (Squire and van der Tak, 1975). But a cost-benefit analysis also often requires the valuation of non-market costs and benefits. This is the case for impacts on public health, cultural heritage, environmental quality and ecosystems, and distributional impacts. Valuation of non-market impact is difficult because of values and preferences heterogeneity, and subject to controversies—for example, on the value to attribute to avoided death (see Viscusi and Aldy, 2003).

There has been progress in valuation of ecosystem services, as elaborated in the Millennium Ecosystem Assessment (MEA, 2005), The Economics of Ecosystems and Biodiversity (TEEB, 2010), and Bateman et al. (2011). Two main categories of approaches have been developed: revealed and stated preference methods. The latter is based on what people say about their preferences, while the former uses their actual decisions (e.g., how

much they pay for a house) and is often considered more accurate. Other approaches include avoided or replacement cost, that is, measuring the cost of providing the ecosystem service artificially. When local information is not available, value transfer techniques can be applied moving information from other locations. For example, Brander et al. (2012) applies value transfer to climate change impacts on wetlands but caution is required in making such transfers (National Research Council, 2005; Navrud and Ready, 2007).

Theoretically, cost-benefit approaches can account for distributional impacts, for instance, through attribution of a higher weight to the poorest (Harberger, 1984). Results are however highly dependent on preferences that can be extremely heterogeneous and difficult to measure (Barsky et al., 1997). As discussed in detail in Chapter 2, valuation and decision making cannot be separated from the institutional and social contexts (e.g., what is considered as a right). Yet, overall, as concluded by the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX), the applicability of rigorous community-based adaptations (CBAs) for evaluations of adaptation to climate variability and change may be limited (Handmer et al., 2012).

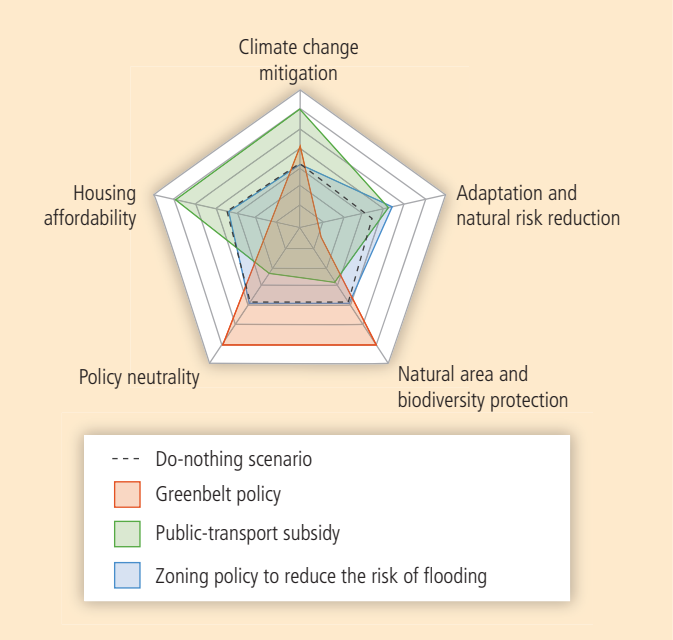

Figure 17-3 | Consequences of three policies in the Paris agglomeration: a greenbelt policy, a public transport subsidy, and a zoning policy to reduce the risk of flooding, measured using five different metrics representing five policy objectives. Axes orientation is such that directions toward the exterior of the radar plot represent positive outcomes (Viguié and Hallegatte, 2012).

17.3.2.2. Multi-Metric Decision Making for Adaptation

Multi-metric decision making provides a broader framework, which also permits balancing among multiple, potentially competing objectives (Keeney and Raiffa, 1993). This branch of decision analysis is also known as multi-criterion analysis. Such an approach is helpful when decision makers have difficulty in trading off different objectives (Martinez-Alier et al., 1998). Using multiple criteria, decision makers can include a full range of social, environmental, technical, and economic criteria—mainly by quantifying and displaying trade-offs. Multi-criterion analyses have been applied to adaptation issues including urban flood risk (Kubal et al., 2009; Grafakos, 2012; Viguie and Hallegatte, 2012), agricultural vulnerability (Julius and Scheraga, 2000), and choice of adaptation options in the Netherlands (Brouwer and van Ek, 2004; de Bruin et al., 2009a), Canada (Qin et al., 2008), and Africa (Smith and Lenhart, 1996). The United Nations Framework Convention on Climate Change (UNFCCC) developed guidelines for the adaptation assessment process in developing countries in which it suggests the use of multi-criteria analysis (UNFCCC, 2002). As an illustration, Figure 17-3 shows a multi-criteria analysis of three urban policies in the Paris agglomeration, using five policy objectives and success indicators (climate change mitigation, adaptation and risk management, natural area and biodiversity protection, housing affordability, and policy neutrality).

17.3.2.3. Non-Probabilistic Methodologies

Cost-benefit analysis and related methods require probabilities for each climate scenario. But in most cases, it may be impossible to define (or to agree on) probabilities for alternative outcomes, or even to identify the set of possible futures (including highly improbable events) (Henry and Henry, 2002; Gilboa, 2010; Millner et al., 2010; Kunreuther et al., 2012). This is especially true for low-probability, high-impact cases or poorly understood risks (Weitzman, 2009; Kunreuther et al., 2012). In such contexts, various approaches have been proposed (see reviews in Ranger et al., 2010; Hallegatte et al., 2012; see also Chapter 2).

Scenario-based analyses study different policies in different scenarios that try and cover the uncertainty space for key parameters (Schwartz, 1996). This is the approach followed by many climate change impact and adaptation studies when using several IPCC *Special Report on Emission Scenarios* (SRES) scenarios (Carter et al., 2001, 2007; Hallegatte et al., 2011). Then, various methodologies or criteria can be used to make a decision.

The *maxi–min* criterion suggests choosing the decision with the best worst-case outcome and the *mini–max regret* criterion (Savage, 1951) suggests choosing the decision with the smallest deviation from optimality in any state of the world. Proposals for "no regrets" adaptation decisions (Callaway and Hellmuth, 2007; Heltberg et al., 2009) employ such criteria. Hybrid criteria balance between optimal and worst case performance (Hurwicz, 1951; Aaheim and Bretteville, 2001; Froyn, 2005).

Another criterion is based on "robustness" and seeks decisions that will perform well over a wide range of plausible climate futures, socioeconomic trends, and other factors (Lempert and Schlesinger, 2000; Lempert et al., 2006; Dessai and Hulme, 2007; Lempert and Collins, 2007; Groves et al., 2008; Wilby and Dessai, 2010; WUCA, 2010; Brown et al., 2011; Lempert and Kalra, 2011). Instead of starting from a few scenarios, these methods start with an option or a project and test it under a large number of scenarios to identify its vulnerabilities to uncertain parameters. Small adjustment or large changes in options or projects can then be identified to minimize these vulnerabilities. Example implementations include InfoGap, which has been used to inform

adaptation decisions in water management (Ben-Haim, 2001; Korteling et al., 2013); RDM (robust decision making), which has been used for water management and flood risk management planning (Lempert et al., 2003; Lempert and Groves, 2010; Lempert and Kalra, 2011; Matrosov et al., 2013); and robust control optimization (Hansen and Sargent, 2008).

Figure 17-4 illustrates the application of robust decision making on flood risks in Ho Chi Minh City (Lempert et al., 2013). The analysis examined different risk management portfolios (including, for instance, raising homes and retreat). Each portfolio was simulated in 1000 scenarios, covering socioeconomic and climate uncertainty. The RDM analysis found that the current plan is robust to a wide range of possible future population and economic trends. But it would keep risk below current levels only if rainfall intensities increase by no more than 5% and if the Saigon River rises less than 45 cm. Additional measures were found that made the situation robust for increases in rainfall intensity of up to 35% and increases in the level of the Saigon River of up to 100 cm.

17.4. Costing Adaptation

Interest in estimating the costs of adaptation has grown as the need for action has become clearer. The literature focuses on two levels of costing: global scale estimates, largely to assess the overall need for adaptation finance funds; and regional and local-scale estimates, often limited to a particular vulnerable economic sector, which may be applied to inform budgeting or to support adaptation decision making, or to allocate scarce resources among the best prospects for effective adaptation. The methods for these two types of studies vary widely, but for the important methodological considerations for costing adaptation are similar for both types.

17.4.1. Methodological Considerations

17.4.1.1. Data Quality and Quantity

There is very little discussion of data gaps related to assessing the benefits of adaptation, but poor or sparse data obviously limit the accuracy of these estimates. Callaway (2004) suggests that a major challenge is the low quality and limited nature of data, especially in many developing countries, and notes many transactions are not reported because they occur in informal economies and social networks. In a more general setting Hughes et al. (2010) note that historical weather data are not typically sufficiently detailed while others note sparse data on costs of adaptation actions. For example, Bjarnadottie et al. (2011) note incomplete and contradictory data on house retrofit costs for hurricane protection. Also there are simply missing non-market data on such items as the value of ecosystem services (Agrawala and Fankhauser, 2008), particularly as affected by climate and possible adaptation.

17.4.1.2. Costs and Benefits Are Location-Specific

Calculating localized impacts requires detailed geographical knowledge of climate change impacts, but these are a major source of uncertainty

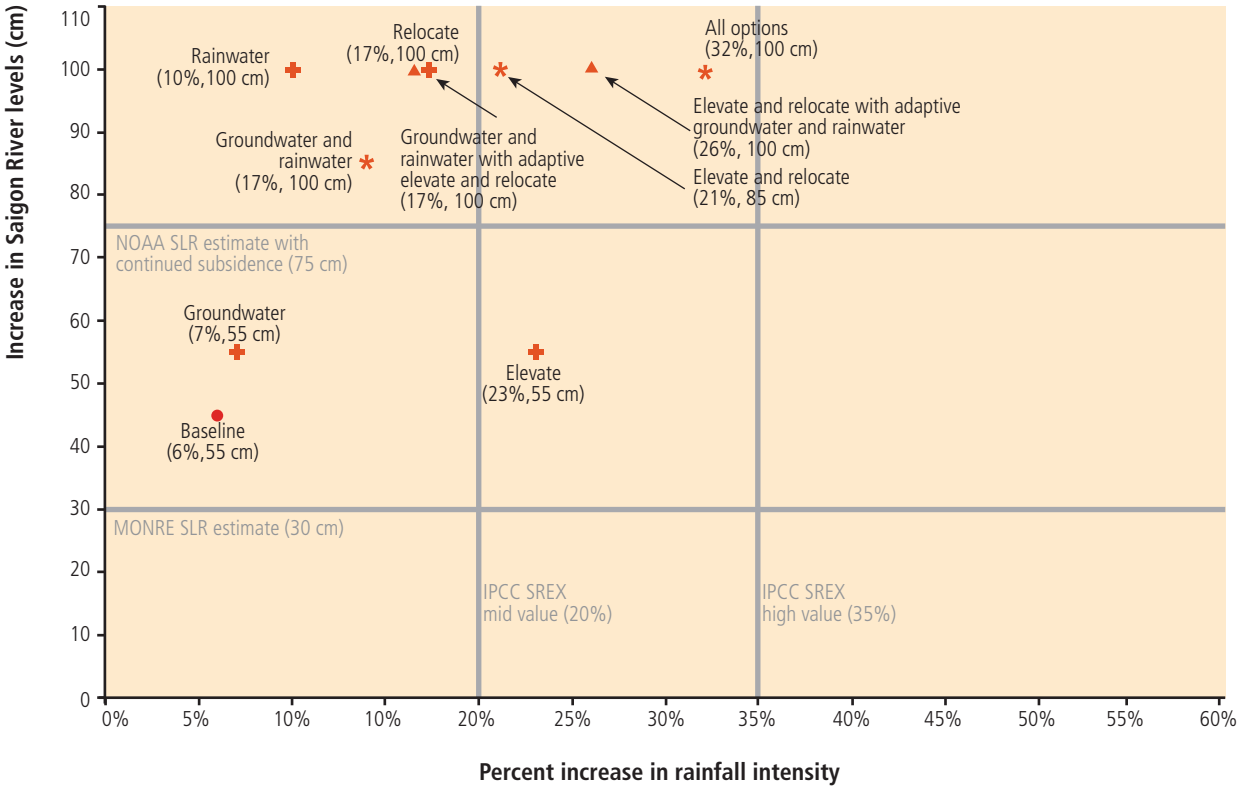

Figure 17-4 | Various risk management strategies in Ho Chi Minh City, and their robustness to increases in river levels and rainfall intensity. Different options can cope with different amplitudes of environmental change (Lempert et al., 2013).

in climate models (see Refsgaard et al., 2013). Global estimates of adaptation cost are generally not grounded in local-scale physical attributes important for adaptation, which in part explains why local and regional-scale adaptation cost estimates are not consistent with global estimates (Agrawala and Fankhauser, 2008). Compared with developed countries, there is also a limited understanding of the potential market sector impacts of climate change in developing countries.

17.4.1.3. Costs and Benefits Depend on Socioeconomics

It is sometimes assumed that climate will change but society will not (Pielke, 2007; Hallegatte et al., 2011; Mechler and Bouwer, 2013). Future development paths affect climate change impact estimates, and can alter estimates from positive to negative impacts or vice versa. Some studies show higher growth rates raise hurricane vulnerability (Bjarnadottir, 2011). On the other hand, higher incomes allow the funding of risk-reducing policies.

17.4.1.4. Discount Rates Matter

Because adaptation costs and consequences occur over time, discount rates are a core question. Opinions vary sharply on this question (Baum, 2009; Heal 2009). Hof et al. (2010) notes that a low discount rate is needed for distant future climate change to matter. A low discount rate is the primary reason for the relatively high estimates of climate damage in the Stern Review (Stern, 2006). For climate adaptation projects, the social or consumption discount rate is the relevant one (Heal, 2009). The rates used fall between 0.1 and 2.5%, although without good arguments for specific values (see Heal, 2009). Nordhaus (2008) chooses a value of 1.5% while Stern uses a much lower value of 0.1%. Nordhaus emphasizes consistency with the rate of return on investment as a driving rationale while Stern points to ethical issues. Allowing environmental services to enter consumption can change the social discount rate substantially and generate a low or even negative social discount rate (Guesnerie, 2004; Sterner and Persson, 2007; Heal, 2009). The UK Treasury now mandates the use of declining discount rates for long-term projects, as suggested by behavioral studies and by theoretical analysis (Arrow et al., 2012).

17.4.2. Review of Existing Global Estimates: Gaps and Limitations

There has been a limited number of global and regional adaptation cost assessments over the last few years (Stern, 2006; World Bank, 2006, 2010a; Oxfam, 2007; UNDP, 2007; UNFCCC, 2007, 2008). These estimates exhibit a large range and have been completed mostly for developing countries. The most recent and most comprehensive to date global adaptation costs range from US$70 to more than US$100 billion annually by 2050 (World Bank, 2010a; see Table 17-2).

IPCC (2012) considers confidence in these numbers to be low because the estimates are derived from only three relatively independent lines of evidence. World Bank (2006) estimates the cost of climate proofing foreign direct investments (FDI), gross domestic investments (GDI), and Official Development Assistance (ODA), as does the Stern Review (2006), Oxfam (2007), and UNDP (2007). UNFCCC (2007) calculated existing and planned investment and financial flows (I&FF), and then estimated the additional investment required for adaptation as a premium on existing and planned investments. The World Bank (2010a) followed the UNFCCC (2007) methodology of estimating the premium climate change imposes on a baseline of existing and planned investment, but included more extensive modeling (as opposed to developing unit cost estimates), constructed marginal cost curves and climate stressor-response functions for adaptation actions, and included maintenance and coastal port upgrading costs.

Given their common approaches these estimates are interlinked, which explains the seeming convergence of their estimates in later years, as discussed by Parry et al. (2009). However, there are important differences in terms of sectoral estimates, as Figure 17-5 shows in comparing the UNFCCC (2007) and World Bank (2010a) studies. Extreme events, a potential source of large adaptation costs, are not properly covered, and these studies take into account a limited set of adaptation options. In addition, the World Bank (2010a) estimates report higher ranges of estimates, reflecting additional effort to account for uncertainty. Parry et al. (2009) consider the UNFCCC (2007) estimates a significant underestimation by at least a factor of two to three plus omitted costs in ecosystem services, energy, manufacturing, retailing, and tourism. Thus the numbers have to be treated with caution. There are a number

Table 17-2 | Estimates of global costs of adaptation.

Study	Results (billion US$ per year)	Time frame	Sectors	Methodology and comments
World Bank (2006)	9–41	Present	Unspecified	Cost of climate proofing foreign direct investments, gross domestic investments, and Official Development Assistance
Stern (2007)	4–37	Present	Unspecified	Update of World Bank (2006)
Oxfam (2007)	>50	Present	Unspecified	World Bank (2006) plus extrapolation of cost estimates from national adaptation plans and NGO projects
UNDP (2007)	86–109	2015	Unspecified	World Bank (2006) plus costing of targets for adapting poverty reduction programs and strengthening disaster response systems
UNFCCC (2007)	28–67	2030	Agriculture, forestry and fisheries; water supply; human health; coastal zones; infrastructure	Planned investment and financial flows required for the international community
World Bank (2010a)	70–100	2050	Agriculture, forestry and fisheries; water supply; human health; coastal zones; infrastructure; extreme events	Improvement on UNFCCC (2007): more precise unit cost, inclusion of cost of maintenance and port upgrading, risks from sea level rise and storm surges

Source: Modified from Agrawala and Fankhauser (2008) and Parry et al. (2009) to include estimates from World Bank (2010a).

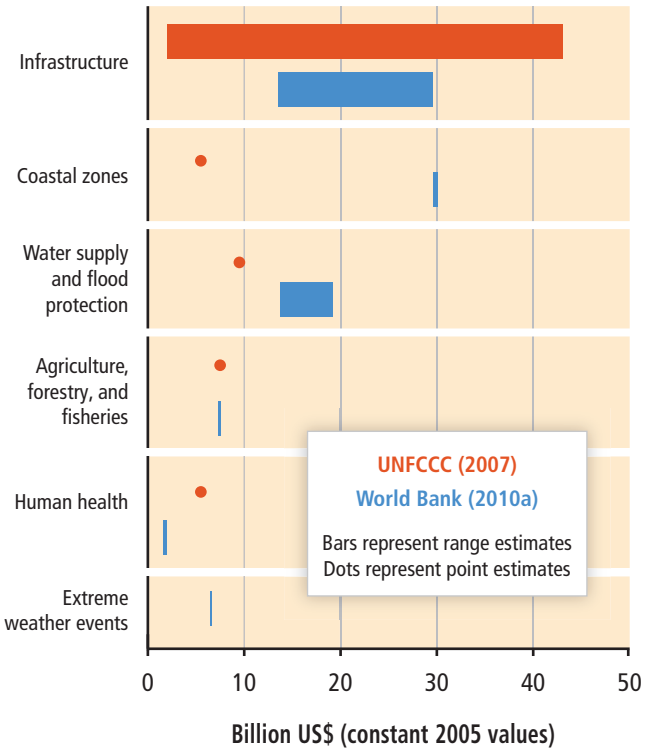

Figure 17-5 | Comparison of sectoral results on the costs of adaptation in developing countries across the UNFCCC and World Bank studies. Note: Bars indicate estimates using ranges; points indicate point estimates.

of gaps, challenges, and omissions associated with those global estimates that merit further discussion.

The practical challenges of conducting global adaptation cost studies are apparent in the literature (as assessed in Parry et al., 2009; World Bank, 2010a; IPCC, 2012). The broad scope of these studies limits the analysis to few climate scenarios, and while the scenarios might be strategically chosen it is difficult to represent fully the range of future adaptation costs across all sectors. The broad scope also limits comprehensive consideration of adaptation options, non-market and co-benefits, equity issues, and adaptation decision making (such limitations also apply to local and regional scale studies; see Section 17.4.3). The global studies, designed to reflect the best available methods and data for the purpose of estimating the magnitude of the global economic adaptation challenge, achieve this limited goal but must be interpreted in light of these important limitations and uncertainties.

17.4.3. Consistency between Localized and Global Analyses

Adaptation costs and benefits are derived to guide specific investment decisions, generally at national and local levels, or to derive a "price tag" for overall funding needs for adaptation (generally at a global level). Given these different purposes it is difficult to compare "local," that is, national and sectoral, with global numbers. The quantity/quality of local studies also varies by sector with more treatment of adaptation in coastal zones and agriculture (Agrawala and Fankhauser, 2008; see Table 17-3). Less is known and many gaps remain for sectors such as water resources, energy, ecosystems, infrastructure, tourism, and public health. Also assessments have predominantly been conducted in a developed country context (see Table 17-1 for examples of costs and benefits assessment).

However, as Fankhauser (2010) notes, with the sole exception of coastal protection costs, adaptation costs have shown little convergence locally or in terms of sectoral to global costs. The World Bank (2010a) study uniquely takes a two-track approach doing parallel national (seven cases) and global adaptation estimates. For a number of country studies (Bangladesh, Samoa, and Vietnam) a cross-country comparison of local and global adaptation costs was made, with the costs in terms of gross domestic product (GDP) found to be in reasonable agreement. Costs for strengthening infrastructure against windstorms, precipitation, and flooding were about 10 to 20% higher compared to disaggregated global estimates, largely owing to the ability of country-level studies to consider at least some socially contingent impacts (World Bank, 2010a,b,c,d). Further, there is evidence of under-investment in adaptation (UNDP, 2007), with global estimates of the need for adaptation funds variously estimated in the range of US$70 to US$100 billion annually (World Bank, 2010a), but with actual expenditures in 2011 estimated at US$244 million (Elbehri et al, 2011), and in 2012 estimated at US$395 million (Schalatek et al., 2012).

17.4.4. Selected Studies on Sectors or Regions

This section focuses on studies that illustrate current practice in estimating adaptation economics, with a particular focus on support of adaptation decision making through economic analysis. Within that class of work, there are two broad categories of economic analyses of adaptation at the sectoral level: econometric and simulation approaches.

Econometric studies generally examine the nature of observed adaptations or the estimation of climate change effects to which farmers have adapted. Such studies rely on observed cross-sectional, time series, or panel data. Examples include those where one implicitly assumes adaptation has occurred linking temperature and precipitation to land values and crop yields or land values (e.g., Mendelsohn et al., 1994; Schlenker et al., 2006) or those identifying adaptations in terms of altered decisions, for

Table 17-3 | Coverage of adaptation costs and benefits.

Sector	Analytical coverage	Cost estimates	Benefit estimates
Coastal zones	Comprehensive	✓✓✓	✓✓✓
Agriculture	Comprehensive	—	✓✓✓
Water	Isolated case studies	✓	✓
Energy	North America, Europe	✓✓	✓✓
Infrastructure	Cross-cutting, partly covered in other sectors	✓✓	—
Health	Selected impacts	✓	—
Tourism	Winter tourism	✓	—

Note: Three checks indicates good to excellent coverage of the topic in the literature; two checks indicates medium coverage; one check indicates limited coverage; the absence of a check indicates extremely limited or no coverage. Note that indicators reflect literature review through publication of source in 2008.

Source: Agrawala and Fankhauser (2008).

Frequently Asked Questions

FAQ 17.2 | Could economic approaches bias adaptation policy and decisions against the interests of the poor, vulnerable populations, or ecosystems?

A narrow economic approach can fail to account adequately for such items as ecosystem services and community value systems, which are sometimes not considered in economic analysis or undervalued by market prices, or for which data are insufficient. This can bias decisions against the poor, vulnerable populations, or the maintenance of important ecosystems. For example, the market value of timber neither reflects the ecological and hydrological functions of trees nor the forest products whose values arise from economic sectors outside the timber industry, like medicines. Furthermore, some communities value certain assets (historic buildings, religious sites) differently than others. Broader economic approaches, however, can attach monetary values to non-market impacts, referred to as externalities, placing an economic value on ecosystem services like breathable air, carbon capture and storage (in forests and oceans), and usable water. The values for these factors may be less certain than those attached to market impacts, which can be quantified with market data, but they are still useful to provide economic assessments that are less biased against ecosystems.

But economic analysis, which focuses on the monetary costs and benefits of an option, is just one important component of decision making relating to adaptation alternatives, and final decisions about such measures are almost never based on this information alone. Societal decision making also accounts for equity—who gains and who loses—and for the impacts of the measures on other factors that are not represented in monetary terms. In other words, communities make decisions in a larger context, taking into account other socioeconomic and political factors. What is crucial is that the overall decision framework is broad, with both economic and non-economic factors being taken into consideration.

A frequently used decision-making framework that provides for the inclusion of economic and non-economic indicators to measure the impacts of a policy, including impacts on vulnerable groups and ecosystems, is multi-criteria analysis (MCA). But as with all decision-making approaches, the challenge for MCA and methods like it is the subjective choices that have to be made about what weights to attach to all the relevant criteria that go into the analysis, including how the adaptation measure being studied impacts poor or vulnerable populations, or how fair it is in the distribution of who pays compared to who benefits.

example, Seo and Mendelsohn (2008a,c) look at enterprise choice, while Mu et al. (2013) look at stocking rate adjustments. Such approaches can also be used to estimate the marginal effect of adaptation, provided that "without adaptation" estimates can be developed (Mendelsohn and Dinar, 2003).

The simulation approach, by contrast, traces costs and benefits of adaptation strategies through mechanisms of interest, typically through a series of climate-biophysical-behavioral response-economic components. Within simulation modeling there are two main threads in the behavioral response-economic component of the simulation. The first involves rational actors who consider the benefit and cost consequences of their choices and pursue economically efficient adaptation outcomes, and the second involves a decision-rule or reference-based characterization of the response of actors to climate stressors (Schlenker et al., 2006; Dinar and Mendelsohn, 2011). As noted later, in many sectors the current practice begins with the simpler decision-rule based approach, and may progress to consider benefits and costs, and then perhaps to consider other factors, such as equity and non-market values.

The key advantages of an econometric approach are reliance on real-world data, the use of "natural experiments" in some cases, and an ability to reflect the joint costs and benefits of multiple adaptation strategies to the extent they are employed together in the real world (Mendelsohn and Neumann, 1999; Dinar and Mendelsohn, 2011). The econometric approach does not require the analyst to simulate all adaptation mechanisms, only to establish that there is a robust relationship between a climate stressor and the outcome of interest. The data required to implement the approach are limited, so the approach can be applied broadly. The key disadvantages of the econometric approach are an inability to trace transmission mechanisms of specific adaptation measures or to isolate the marginal effect of these strategies or measures; the inability to transfer estimates out of context (e.g., an African study does not apply to Asia, where the climate, adaptation, and social context all differ and affect the marginal costs and benefits of adaptation measures); and that the statistical estimation can be challenging and sometimes subject to multiple interpretations (Schlenker et al., 2005).

Simulation modeling can be demanding—a key disadvantage—as it requires extensive data inputs and careful calibration. Where data and models are available, however, the simulation modeling method works well. For example, an agricultural adaptation modeling system can estimate such factors as the incremental change in crop output and water

Table 17-4 | Studies illustrating economic evaluation of adaptation options.

Sector	Study and scope	Methodology	Key points illustrated
Agriculture, forestry, and livestock	Seo and coinvestigators (e.g., Seo et al., 2008b, 2009b, 2011): Impacts to livestock producers in Africa	Econometric. Examines the economic choices that livestock owners make to maintain production in the face of climate. Insights into adaption possibilities are achieved by examining the ways economic choices vary over locations and times with varying climate conditions.	• Consideration of multiple options (implicit) • Residual impacts reflected • Applicable at multiple geographic scales • Results provide a ready means to re-estimate results for multiple climate scenarios.
	Butt et al. (2006): Crop sector in Mali	Simulation. Simulates the economic implications of potential adaptation possibilities. Examines the consequences of migration in cropping patterns, development of heat resistant cultivars, reduction in soil productivity loss, cropland expansion, and changes in trade patterns.	• Broad consideration of options (explicit, allowing for ranking of measures) • Residual impacts reflected • Rigorous economic costing of adaptation options and consequences for yields, revenue, and food security
	Sutton et al. (2013): Crop and livestock sector in four eastern European and central Asian countries	Simulation with benefit/cost analysis. Ranks options initially based on net economic benefits over 2010–2050 period. Considers non-market and socially contingent effects through stakeholder consultation process.	• Broad consideration of options (explicit, measures ranked) • Very broad representation of climate scenarios (56 General Circulation Model–Special Report on Emission Scenarios combinations) • Rigorous economic costing of adaptation options • Integrated analysis of agriculture and irrigation water sectors
Sea level rise and coastal systems	Nichols and Tol (2006): Coastal regions at a global scale	Simulation of adaptation through construction of seawalls and levees, adoption of beach nourishment to maintain recreational value, and migration of coastal dwellers from vulnerable areas. The study reflects an economic decision rule for most categories and benefit/cost analysis for a few categories	• Capable of broad representation of sea level rise scenarios • Optimization of alternatives considering both the impact of adaptation and resulting residual impacts • Rigorous economic costing of adaptation options
	Neumann et al. (2010a): Risks of sea level rise for a portion of the coastal United States	Simulation of adaptation decision making including seawalls, bulkheads, elevation of structures, beach nourishment, and strategic retreat, primarily using a benefit/cost framework but with alternatives based on local land use decision-making rules	• Capable of broad representation of sea level rise scenarios • Flexibility to consider both benefit/cost and rule-based decision making • Rigorous and dynamic economic costing of adaptation options
	Purvis et al. (2008): Risks of coastal flooding in Somerset, England	Simulation using a probabilistic representation to characterize uncertainty in future sea level rise and, potentially, other factors that could affect coastal land use planning and development investment decisions	• Considers the impact of both gradual climate change (sea level rise) and extreme events (the 1-in-200-year recurrence interval coastal flooding event) • Incorporates probabilistic uncertainty analysis
Water	Ward et al. (2010): Future needs and costs for municipal water across the world, scalable to national and local scales	Assesses costs with and without climate change of reaching a water supply target in 2050. The aggregation level used is the food producing units level, and storage capacity change, using the secant peak algorithm to determine the storage yield relationship and the cost of various alternative sources of water. The authors find that baseline costs exceed adaptation costs ($73 billion per year versus $12 billion per year for adaptation), with most of the adaptation costs (83–90%) incurred in developing countries.	• Multiple climate scenarios • Scalable to multiple spatial resolutions, with national and regional results reported • Multiple alternative adaptation options considered • Rigorous economic costing of site-specific capital and operating costs
Urban flooding	Ranger et al. (2011): direct and indirect impacts of flooding in Mumbai, India	Investigates the consequences of floods with different return periods, with and without climate change; the effect of climate change is from a weather generator that downscales simulations from a global climate model. Estimates direct losses from a 100-year event rising from $600 million today to $1890 million in the 2080s, and total losses (including indirect losses) rising from $700 to $2435 million. Impacts give rise to adaptation options, some targeting direct losses (e.g., improved building quality, improved drainage infrastructure) and others targeting indirect losses (e.g., increased reconstruction capacity, micro-insurance). Analysis finds that improved housing quality and drainage could bring total losses in the 2080s below current levels and that full access to insurance would halve indirect losses for large events.	• Considers multiple adaptation options • Explicitly considers both direct and indirect costs • Rigorous economic costing of adaptation options
Energy	Lucena et al. (2010): Energy production in Brazil, particularly from hydropower	Simulation of multiple adaptation options, including energy source substitution and regional "wheeling" of power coupled with modeling of river flow and hydropower production under future climatic conditions. Uses an optimization model of overall energy production.	• Considers two greenhouse gas emissions scenarios and a "no-climate change" baseline • Scalable to multiple spatial resolutions, with national and regional results reported • Considers multiple adaptation strategies • Rigorous economic costing of capital and recurring adaptation costs
Health	Ebi (2008): Global adaptation costs of treatment of diarrheal diseases, malnutrition, and malaria	The costs of three diseases were estimated in 2030 for three climate scenarios using (1) the current numbers of cases; (2) the projected relative risks of these diseases in 2030; and (3) current treatment costs. The analysis assumed that the costs of treatment would remain constant. There was limited consideration of socioeconomic development.	• Multiple climate scenarios • Clear description of framework and key assumptions • Rigorous economic costing of adaptation options using multiple assumptions to characterize uncertainty

Continued next page →

Table 17-4 (continued)

Sector	Study and scope	Methodology	Key points illustrated
Macroeconomic analysis	De Bruin et al. (2009b): Adaptation strategies compared to mitigation strategies within the context of a global integrated assessment model	Use of an integrated assessment model (the DICE model) with refined adaptation functions. Examines the efficacy of "stock" adaptations (mainly infrastructure) adaptations versus "flow" adaptations (mainly operational or market responses), with comparisons to mitigation investments.	• Multiple climate scenarios • Clear description of framework and key assumptions • Considers multiple adaptation strategies • Rigorous economic costing of adaptation options
	Margulis et al. (2011): Climate change impacts in the economy	Use of a general equilibrium model to simulate two climate change-free scenarios regarding the future of Brazil's economy. Climate shocks were projected and captured by the model through impacts on the agricultural/ livestock and energy sectors. The socioeconomic trends of the scenarios with and without global climate change were reviewed in terms of benefits and costs for Brazil and its regions.	• The economic impacts of climate change are experienced across business sectors, regions, states, and large cities and were expressed in terms of gross domestic product losses. • The simulation disaggregates results for up to 55 sectors and 110 products and also provides macroeconomic projections such as inflation, exchange rate, household sector consumption, government expenditures, aggregate investment, and exports. It also includes expert projections and scenarios on specific preferences, technology, and sector policies.

supply in response to changes in climatic conditions and agricultural and water resource management techniques. A further advantage of the simulation approach is that it provides an opportunity for stakeholder involvement at several stages of the analytic process: designing scope, adjusting parameters, selecting inputs, calibrating results, and incorporating adaptation measures of specific local interest (Dinar and Mendelsohn, 2011).

A wide range of studies attempt an economic evaluation of adaptation options. From these, several desirable characteristics can be identified:

- A broad representation of climate stressors, including both gradual change and extreme events, spanning multiple future outcomes (e.g., a range of individual climate model forecasts and greenhouse gas emissions scenarios). Consideration of multiple outcomes reflects forecasting uncertainty and can help to ensure the adaptation rankings that result from the analysis are robust across a range of future outcomes (Lempert and Kalra, 2009; Agrawala et al., 2011; see also Chapter 2).
- Representation of a wide variety of alternative adaptation responses (e.g., in the agriculture sector, consideration of changes in crop varieties and farmer education to ensure the varieties are grown with the best available know-how). Depending on the context, single adaptation response with variation in dimension may be useful (e.g., varying the height of a levee or the capacity of a dam spillway) (Fankhauser et al., 1999; Fankhauser, 2010; World Bank, 2010a).
- Rigorous economic analysis of costs and benefits, which ideally includes consideration of market, non-market, and socially contingent implications (Watkiss, 2011); one-time and replacement capital and ongoing recurring costs; and costs of residual damages after an adaptation response is implemented (World Bank, 2010a).
- A strong focus on adaptation decision making, including a clear exposition of the form of adaptation decision making that is implied in the study, and consideration of both climate and non-climate sources of uncertainty (Lempert et al., 2006; see also Chapter 2).

Table 17-4 highlights studies that illustrate some of these characteristics. The studies include both simulation studies of the economic implications of adaptation options, and econometric ones that examine choices that producers make to adapt. These studies generally fall in the category of positive economics, where economic tools and analysis are used to examine the implications of alternative choices without imposing values of the author (see Friedman, 1953). A few studies incorporate a normative perspective, either explicitly or implicitly, reflecting value judgments of authors or study participants.

17.5. Economic and Related Instruments to Provide Incentives

Through regulations, subsidies, and direct intervention, there are many opportunities for policymakers to encourage autonomous adaptation. However, these efforts need to be designed so as to yield efficient, cost-effective responses while avoiding perverse results. A basic issue of designing efficient policies is to understand that they affect the behavior of those who have the most to gain. For this and other reasons, economists tend to favor policies based on voluntary actions influenced by incentives, either positive or negative, over mandates or uniform policies. Examples of these include insurance markets, water markets, and various payments for environmental services (PES) schemes. A second consideration in policy design is cost effectiveness, that is, the extent to which governments make the best use of their resources. The measurement of the net effect of a policy is challenging because it is difficult to anticipate what would have occurred without the policy.

Finally, policies must be carefully designed to avoid perverse outcomes that run counter to the policymaker's objectives. A classic example is found in policies that encourage adoption of water-saving technology. Pfeiffer and Lin (2010) review cases where subsidizing irrigation water conservation leads farmers to increase total water use by increasing the acreage under irrigation. This is an example of what is often called the rebound effect (Roy, 2000), whereby increases in efficiency of resource use result in more being demanded.

With the exception of insurance- and trade-related instruments there is relatively little literature on the use of economic instruments for adaptation (see Chapter 10). One reason is that, apart from insurance, few adaptation policies work directly via economic incentives and markets. The potential of economic instruments in an adaptation context is, however,

widely recognized. In line with Agrawala and Fankhauser (2008), we distinguish, among others, the following incentive-providing instruments relevant for key sectors: (1) insurance schemes (all sectors; extreme events); (2) price signals/markets (water, ecosystems); (3) regulatory measures and incentives (building standards, zone planning); and (4) research and development incentives (agriculture, health).

17.5.1. Risk Sharing and Risk Transfer, Including Insurance

Insurance-related formal and informal mechanisms can directly lead to adaptation and provide incentives or disincentives. Informal mechanisms include reliance on national or international aid or remittances, and though such mechanisms are common, they tend to break down for large, covariate events (Cohen and Sebstad, 2005). Another informal mechanism is the inclusion of climate change risk under corporate disclosure regulations (National Round Table on the Environment and the Economy, 2012). Formal mechanisms include insurance, micro-insurance, reinsurance, and risk pooling arrangements. Insurance typically involves ongoing premium payments in exchange for coverage and post event claim payments. In contrast to indemnity-based insurance, index-based insurance insures the event (as, e.g., measured by lack of rainfall), not the loss, and is a possibility for providing a safety net without moral hazard, yet suffers from basis risk, the lack of correlation of loss to event (Collier et al. 2009; Hochrainer et al., 2009; see also Section 10.7 for a supply-side-focused perspective on insurance). Markets differ substantially according to how liability and responsibility is distributed (Aakre et al., 2009; Botzen et al., 2009), and in many instances governments play a key role as regulators, insurers, or reinsurers (Linnerooth-Bayer et al., 2005). Insurance penetration in developed countries is considerable, whereas it is low in many developing regions. In the period 1980–2004 about 30% of losses were insured in high-income countries, but only about 1% in low-income countries (Linnerooth-Bayer et al., 2011). Developing countries are beginning to pool risks and transfer portions to international reinsurance markets. The Caribbean Catastrophic Risk Insurance Facility (CCRIF) set the precedent by pooling risks basin wide, thus reducing insurance premiums against hurricane and earthquake risks (World Bank, 2007). Similar schemes are under development planning in Europe, Africa, and the Pacific (Linerooth-Bayer et al., 2011).

Insurance-related instruments may promote adaptation directly and indirectly: (1) Instruments provide claim payments after an event, and thus reduce follow-on risk and consequences; and (2) they alleviate certain pre-event risks and allow for improved decisions (Hess and Syroka, 2005; Hoppe and Gurenko, 2006; Skees et al., 2008). As one interesting example, using crop micro-insurance linked to loans, farmers exposed to severe drought in Malawi were able to grow higher-yield, yet higher-risk crops, which allowed them to increase incomes (Linnerooth-Bayer and Mechler, 2011).

The indirect effects occur via the provision of incentives and disincentives. Premiums for risk coverage can provide an incentive to reduce the premium by reducing the risk. In practice, the incentive effect is generally weak. Kunreuther et al. (2009) found that insurance decisions are not based solely on costs and premiums, but also desires to reduce anxiety, comply with mortgage requirements, and satisfy social norms. Further, purchasing insurance may reduce adaptation with insured agents reducing their risk-minimizing efforts after taking out coverage. This is termed moral hazard and has been found to be rational (Kunreuther, 1998). Moral hazard can be reduced through the use of index-based insurance, although this has the drawback of operating from a high base risk (Collier et al., 2009; Hochrainer et al., 2009). Another difficulty arises when local or state regulations undermine incentives to decrease risk (for instance, by not allowing insurance rates to be fully risk adjusted). Some analysts suggest the removal of existing regulations that distort market signals in order to re-align incentives, yet this is likely to be ineffective given that the incentive effect is not considered very strong and often premiums are not fully risk-based (Michel-Kerjan and Kunreuther, 2011). Also, Rao and Hess (2009) argue there is the possibility that some current insurance schemes may increase maladaptation. Under-insurance can also arise when agents expect that the public sector will provide disaster assistance. Some refer to this as the Samaritan's dilemma (Gibson et al., 2005; Raschky et al., 2013).

17.5.2. Payments for Environmental Services

Payments for environmental services (PES) pay landholders or farmers for actions that preserve the services to public and environmental health provided by ecosystems on their property, including services that contribute to both climate change adaptation and mitigation. There are ample cases of mitigation-focused PES schemes (e.g., Pagiola, 2008; Wunder and Albán, 2008; Wunder and Borner, 2011), and more recently emerging evidence of the use of PES in adaptation which are of pilot nature and location-specific, however (Butzengeiger-Geyer et al., 2011; Schultz, 2012; van de Sand, 2012). Potentially well designed PES schemes offer a framework for adaptation and there is a view among development agencies that with more experience and guidance on implementation PES might well contribute to adaptation as one of a multitude of feasible measures (e.g., taxes, charges, subsidies, loans). Chishakwe et al. (2012) draw comparisons and find synergies between PES community-based natural resources management approaches in southern Africa and community-based adaptation.

17.5.3. Improved Resource Pricing and Water Markets

Studies of water sector adaptation often begin by citing the implications of future water shortages and the potential for conflict. Techniques frequently cited for resolving these conflicts include the establishment of water markets or water pricing schemes (e.g., Vorosmarty et al., 2000; Adler, 2008; Alavian et al., 2009), which is in itself, however, also often associated with conflict (Miller et al., 1997). Traditionally water markets facilitate transfer from lower to higher-valued uses (Olmstead, 2010) but pricing rules can also function through urban fees and real estate taxes (as they do for water supply and urban stormwater regulation in many countries). A few studies make the case that water markets and pricing improves climate change adaptation (Medellin-Azuara et al., 2008). In many cases, the projected increase in climate-induced water demand (particularly in the agriculture sector), coupled with a projected decrease in water supply, suggests that adaptation will be needed.

Many countries have instituted structures for water pricing in the household and agricultural sectors. Nevertheless such prices are unevenly

Frequently Asked Questions

FAQ 17.3 | In what ways can economic instruments facilitate adaptation to climate change in developed and developing countries?

Economic instruments (EIs) are designed to make more efficient use of scarce resources and to ensure that risks are more effectively shared between agents in society. EIs can include taxes, subsidies, risk sharing, and risk transfer (including insurance), water pricing, intellectual property rights, or other tools that send a market signal that shapes behavior. In the context of adaptation, EIs are useful in a number of ways.

First, they help establish an efficient use of the resources that will be affected by climate change: water pricing is an example. If water is already priced properly, there will be less overuse that has to be corrected through adaptation measures should supplies become more scarce.

Second, EIs can function as flexible, low-cost tools to identify adaptation measures. Using the water supply example again, if climate change results in increasing water scarcity, EIs can easily identify adjustments in water rates needed to bring demand into balance with the new supply, which can be less costly than finding new ways to increase supply.

Insurance is a common economic instrument that serves as a flexible, low-cost adaptation tool. Where risks are well defined, insurance markets can set prices and insurance availability to encourage choices and behaviors that can help reduce vulnerability, and also generate a pool of funds for post-disaster recovery. Insurance discounts for policy holders who undertake building modifications that reduce flood risk, for example, are one way that EIs can encourage adaptive behavior.

Payments for environmental services (PES) schemes are another economic instrument that encourages adaptive behavior. This approach pays landholders or farmers for actions that preserve the services to public and environmental health provided by ecosystems on their property, including services that contribute to both climate change mitigation and adaptation. A PES approach is being used in Costa Rica to manage natural resources broadly, for example. Paying timber owners not to cut down forests that serve as carbon sinks (the idea behind the Reduced Emissions from Deforestation and Forest Degradation (REDD) proposal to the United Nations Framework Convention on Climate Change (UNFCCC)) or paying farmers not to cultivate land in order reduce erosion damage (as is being done in China and the USA) are examples. In developed countries, where markets function reasonably well, EIs can be directly deployed through market mechanisms. In developing countries (and also in some developed ones), however, this is not always the case and markets often need government action and support. For example, private insurance companies sometimes don't cover all risks, or they set rates that are not affordable, and public intervention is required to make sure the insurance is available and affordable. Government also has an important role in ensuring that voluntary market instruments work effectively and fairly, through legal frameworks that define property rights involving scarce resources such as land and water in areas where such rights are not well established. An example of this is the conflict between regions over the use of rivers for water supply and hydropower, when those rivers flow from one jurisdiction to the next and ownership of the water is not clearly established by region-wide agreements. PES schemes can only function well when the public sector ensures that rights are defined and agreements honored.

applied, collection rates are low, metering is rarely implemented (at least for the agricultural sector, which is typically the largest water user), and pricing is often based on annual rather than usage-based fees (Saleth et al., 2012). In many countries, a number of important institutional barriers to water markets and pricing remain. These include a lack of property rights including a thorough consideration of historical and current entitlements, limits on transferability, legal and physical infrastructures, and institutional shortcomings (Turral et al., 2005; Saleth et al., 2012) coupled with issues involved with return flows, third-party impacts, market design, transactions costs, and average versus marginal cost pricing (Griffin, 2012).

17.5.4. Charges, Subsidies, and Taxes

The environmental economics literature over the past 30 years has emphasized the importance of market-based instruments (MBIs) relative to command and control regulations. MBIs are shown to be generally more cost effective, providing stronger incentives for innovation and dynamic efficiency. Within the wide range of instruments that qualify as market based, there is a general preference in terms of overall efficiency for taxes over subsidies (Sterner, 2002; Barbier and Markandya, 2012). MBIs include charges on harmful emissions and wastes, subsidies to clean energy, subsidized loans, and others.

In many cases climate change exacerbates the effects of pricing resources below their social costs. This is true for some forms of energy (e.g., hydro- and fossil fuel-based) as well as many ecosystem services. If these resources were optimally priced, there would be greater incentives to investment in clean technologies and the need for additional public sector adaptation measures would be lessened (ESMAP, 2010).

In addition to the instruments already identified, others that are potentially important include raising the price of energy through a tax (Sterner, 2011), developing markets for genetic resources (Markandya and Nunes, 2012), and strengthening property rights so schemes such as PES can be more effective. These measures are desirable even in the absence of climate change; they become even more so when climate impacts are accounted for. Yet it is important to note that though the case for such social cost pricing through the use of charges is strong, it also has its limitations. Higher prices for key commodities can hurt the poor and vulnerable and complementary measures may need to be taken to address such effects.

17.5.5. Intellectual Property Rights

Technology transfer is increasingly seen as an important means of adaptation because of the global benefits it provides through the transfer of knowledge. Christiansen et al. (2011), in a Technology Needs Assessments carried out in developing countries, list about 165 technological needs related to mitigation and adaptation. Examples include applications to agriculture in Cambodia and Bangladesh and coastal zones in Thailand. In many of these cases patents and other intellectual property protection constrain technology transfer. Patent buy-outs, patent pools, compulsory licenses, and other open source approaches have been used to relax this constraint (Dutz and Sharma, 2012). Patent buy-outs involve third parties (e.g., international financial institutions or foundations) acquiring the marketing rights for a patented product in a developing country. Patent pools represent a group of patent holders who agree to license their individual patents to each other (closed pool) or to any party (open pool). Compulsory licenses are issued by governments and allow patent rights to be overridden in critical situations. For all the above reasons, therefore, it is suggested that limits to technology transfer are limiting climate change adaptation (Henry and Stiglitz, 2010). There is also the view, however, that strong intellectual property (IP) protection in receiving countries is facilitating technology transfer from advanced countries, and the evidence indicates a systematic impact of IP protection on technology transfer through exports, FDI, and technology licensing, particularly for middle-income countries for which the risk of imitation in the absence of such protection is relatively high.

17.5.6. Innovation and Research & Development Subsidies

Subsidies to encourage innovation through research and development (R&D) may be employed as a measure to encourage adaptation investments as well as behavioral change (Bräuninger at al., 2011). Subsidies involve direct payments, tax reductions, or price supports that enhance the rewards from the implementation of an activity (Gupta et al., 2007). There has been some criticism of the efficiency of subsidies in terms of rent seeking and adverse effects on competitiveness (Barbier and Markandya, 2012). They are often poorly targeted and end up getting captured by middle and upper income groups. Moreover, they imply increasing budgetary burdens. Yet they are popular with decision makers and the wider public. Subsidies are today mostly used for reasons other than climate adaptation, and evidence regarding its use for adaptation as well as regarding the incentivizing of adaptation R&D specifically is missing. Popp (2004) is partly an exception, which focuses on subsidies for mitigation. It shows that such subsidies have little impact on their own but they do work to enhance the effects of other instruments such as energy taxes and regulations that mandate improvements in energy efficiency and the use of lower carbon options.

17.5.7. The Role of Behavior

It is well recognized that often human behavior is characterized by bounded rationality, particularly in relation to choices under risk and uncertainty, which affects the effectiveness of incentive-based approaches. Individuals may over- or underestimate risks (Ellsberg, 1961; Kahneman and Tversky, 1979), and may not consistently weigh long-term consequences (Ainslie, 1975). One well documented explanation is that individuals do not fully use available information on risks when they make their choices (Magat et al., 1987; Camerer and Kunreuther, 1989; Hogarth and Kunreuther, 1995). Policies that well consider such risk perceptions and behavioral biases increase their efficiency. For instance, people react differently to abstract information on distant events as opposed to concrete, current, emotionally charged information (Trope and Liberman, 2003). In practice, this can limit the impact of simply communicating "dry," emotion-free information, such as that on flood return periods, and underlines the importance of participatory, reflexive, and iterative approaches to decision support (Fischhoff et al., 1978; Slovic, 1997; Renn, 2008; IRGC, 2010; see also Section 2.1.2).

References

Aaheim, H.A. and C. Bretteville, 2001: *Decision-Making Frameworks for Climate Policy under Uncertainty*. Working Paper 2001-02, Center for International Climate and Environmental Research (CICERO), Oslo, Norway, 30 pp.

Aakre, S. and D.T. Rübbelke, 2010: Adaptation to climate change in the European Union: efficiency versus equity considerations. *Environmental Policy and Governance*, **20(3)**, 159-179.

Aakre, S., I. Banaszak, R. Mechler, D. Rübbelke, A. Wreford, and H. Kalirai, 2009: Financial adaptation to disaster risk in the European Union: improving roles for the public sector. *Mitigation and Adaptation Strategies for Global Change*, **15(7)**, 721-736, doi:10.1007/s11027-010-9232-3.

Adger, W.N., 2003: Social capital, collective action, and adaptation to climate change. *Economic Geography*, **79 (4)**, 387-404.

Adger, W.N., N.W. Arnell, and E.L. Tompkins, 2005a: Successful adaptation to climate change across scales. *Global Environmental Change*, **15(2)**, 77-86.

Adger W.N., K. Brown, and E.L. Tompkins, 2005b: The political economy of cross-scale networks in resource co-management. *Ecology and Society*, **10(2)**, 9, www.ecologyandsociety.org/vol10/iss2/art9/.

Adger, W.N., J. Paavola, S. Huq, and M.J. Mace (eds.), 2006: *Fairness in Adaptation to Climate Change*. MIT Press, Cambridge, MA, USA, 319 pp.

Adger, W.N., S. Agrawala, M.M.Q. Mirza, C. Conde, K. O'Brien, J. Pulhin, R. Pulwarty, B. Smit, and K. Takahashi, 2007: Assessment of adaptation practices, options, constraints and capacity. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment*

Report of the Intergovernmental Panel on Climate Change [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)] Cambridge University Press, Cambridge, UK and New York, NY, USA, 717-743.

Adger, W.N., S. Dessai, M. Goulden, M. Hulme, I. Lorenzon, D.R. Nelson, L.O. Naess, J. Wolf, and A. Wreford, 2009: Are there social limits to adaptation to climate change? *Climatic Change*, **93**, 335-354.

Adler, J.H., 2008: Water marketing as an adaptive response to the threat of climate change. *Hamline Law Review*, **31(3)**, 729-754.

Agrawala, S. and S. Fankhauser (eds.), 2008: *Economic Aspects of Adaptation to Climate Change: Costs, Benefits and Policy Instruments*. OECD Publishing, Paris, France, 134 pp.

Agrawala, S., F. Bosello, C. Carraro, E. de Cian, and E. Lanzi, 2011: Adapting to climate change: costs, benefits, and modelling approaches. *International Review of Environmental and Resource Economics*, **5(3)**, 245-284.

Ainslie, G., 1975: Specious reward: a behavioral theory of impulsiveness and impulse control. *Psychological Bulletin*, **82(4)**, 463-496.

Alavian, V., H.M. Qaddumi, E. Dickson, S.M. Diez, A.V. Danilenko, R.F. Hirji, G. Puz, C. Pizarro, M. Jacobsen, and B. Blankespoor, 2009: *Water and Climate Change: Understanding the Risks and Making Climate-Smart Investment Decisions.* The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 140 pp.

Alston, J.M. and B.H. Hurd, 1990: Some neglected social costs of government spending in farm programs. *American Journal of Agricultural Economics*, **72 (1)**, 149-156.

Arrow, K.J. and A.C. Fisher, 1974: Environmental preservation, uncertainty, and irreversibility. *Quarterly Journal of Economics*, **88**, 312-319.

Arrow, K.J., M.L. Cropper, G.C. Eads, R.W. Hahn, L.B. Lave, R.G. Noll, P.R. Portney, M. Russel, R.L. Schmalensee, V.K. Smith, and R.N. Stavins, 1996: *Benefit-Cost Analysis in Environmental, Health, and Safety Regulation*. American Enterprise Institute for Public Policy Research (AEI), The Annapolis Center, and Resources for the Future, AEI Press, c/o Publisher, Resources, Inc., La Verge, TN, USA, 18 pp.

Arrow, K., M. Cropper, C. Gollier, B. Groom, G. Heal, R. Newell, W. Nordhaus, R. Pindyck, W. Pizer, P. Portney, T. Sterner, R.S.J. Toll, and M. Weitzman, 2013: Policy Forum: Determining benefits and costs for future generations. *Science*, **341(6144)**, 349-350.

Asquith, N., M.T. Vargas, and S. Wunder, 2008: Selling two environmental services: in-kind payments for bird habitat and watershed protection in Los Negros, Bolivia. *Ecological Economics*, **65**, 675-684.

Atkinson, A.B. and J.E. Stiglitz, 1980: *Lectures in Public Economics*. McGraw-Hill Book Company, Singapore, 619 pp.

Attavanich, W., B.A. McCarl, Z. Ahmedov, S.W. Fuller, and D.V. Vedenov, 2013: Climate change and infrastructure: effects of climate change on U.S. grain transport. *Nature Climate Change*, **3**, 638-643.

Barbier, E.B. and A. Markandya, 2012: *A New Blueprint for a Green Economy*. Routledge, Abingdon, UK and New York, NY, USA, 216 pp.

Barr, R., S. Fankhauser, and K. Hamilton, 2010: Adaptation investments: a resource allocation framework. *Mitigation and Adaptation Strategies for Global Change*, **15(8)**, 843-858, doi:10.1007/s11027-010-9242-1.

Barsky, R.B., F.T. Juster, M.S. Kimball, and M.D. Shapiro, 1997: Preference parameters and behavioral heterogeneity: an experimental approach in the health and retirement study. *The Quarterly Journal of Economics*, **112(2)**, 537-579.

Bateman, I.J., R. Brouwer, S. Ferrini, M. Schaafsma, D.N. Barton, A. Dubgaard, B. Hasler, S. Hime, I. Liekens, S. Navrud, L. De Nocker, R. Ščeponavičiūtė, and D. Semėnienė, 2011: Making benefit transfers work: deriving and testing principles for value transfers for similar and dissimilar sites using a case study of the non-market benefits of water quality improvements across Europe. *Environmental and Resource Economics*, **50**, 365-387.

Batterbury, S., 2008: Anthropology and global warming: the need for environmental engagement. *Australian Journal of Anthropology*, **1**, 62-67.

Baum, S.D., 2009: Description, prescription and the choice of discount rates. *Ecological Economics*, **69 (1)**, 197-205.

Baumol, W.G. and W.E. Oates, 1975: *The Theory of Environmental Policy: Externalities Public Outlays, and the Quality of Life*. Prentice-Hall, Inc., Englewood Cliffs, NJ, USA, 272 pp.

Baylis, K., S. Peplow, G. Rausser, and L. Simon, 2008: Agri-environmental policies in the EU and United States: a comparison. *Ecological Economics*, **65**, 753-764.

Becken, S., 2005: Harmonising climate change adaptation and mitigation: the case of tourist resorts in Fiji. *Global Environmental Change*, **15(4)**, 381-393.

Beckman, M., 2011: Converging and conflicting interests in adaptation to environmental change in Central Vietnam. *Climate and Development*, **3(1)**, 32-41.

Bell, M., R. Goldberg, C. Hogrefe, P.L. Kinney, K. Knowlton, B. Lynn, J. Rosenthal, C. Rosenzweig, and J. Patz, 2007: Climate change, ambient ozone, and health in 50 US cities. *Climatic Change*, **82**, 61-76.

Belton, V. and T.J Stewart, 2002: *Multiple Criteria Decision Analysis: An Integrated Approach*. Springer Science, Dordrecht, Netherlands, 372 pp.

Beltratti, A., G. Chichilnisky, and G. Heal, 1998: Uncertain future preferences and conservation. In: *Sustainability: Dynamics and Uncertainty* [Chichilnisky, G., G.M. Heal, and A. Vercelli (eds.)]. Vol. 9 of Fondazione Eni Enrico Mattei (FEEM) series on economics, energy, and environment, Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 257-275.

Ben-Haim, Y., 2001: *Information-Gap Decision Theory: Decisions under Severe Uncertainty*. Academic Press, San Diego, CA, USA, 330 pp.

Berkhout, F., J. Hertin, and D.M. Gann, 2006: Learning to adapt: organisational adaptation to climate change impacts. *Climatic Change*, **78(1)**, 135-156.

Bernstein, P., 1996: *Against the Gods: The Remarkable Story of Risk*. John Wiley & Sons, Hoboken, NJ, USA, 383 pp.

Biesbroek, R., J. Klostermann, C. Termeer, and P. Kabat, 2011: Barriers to climate change adaptation in the Netherlands. *Climate Law*, **2(2)**, 181-199.

Birthal, P.S., S.N. Nigam, A.V. Narayanan, and K.A. Kareem, 2011: *An Economic Assessment of the Potential Benefits of Breeding for Drought Tolerance in Crops: A Case of Groundnut in India*. Research Bulletin No. 25, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Andhra Pradesh, India, 36 pp., ec2-50-19-248-237.compute-1.amazonaws.com/285/1/115-2011_RB25_an_econ_assess.pdf.

Bizikova, L., S. Burch, S. Cohen, and J. Robinson, 2010: Linking sustainable development with climate change adaptation and mitigation. In: *Climate Change, Ethics and Human Security* [O'Brien, K., A. St. Clair, and B. Kristoffersen (eds.)]. Cambridge University Press, Cambridge, UK, pp. 157-179.

Bjarnadottir, S., Y. Li, and M.G. Stewart, 2011: A probabilistic-based framework for impact and adaptation assessment of climate change on hurricane damage risks and costs. *Structural Safety*, **33(3)**, 173-185.

Blaikie, P., B. Wisner, T. Cannon, and I. Davis, 1994: *At Risk: Natural Hazards, People's Vulnerability and Disaster*. 1st edn., Routledge, Abingdon, UK and New York, NY, USA, 284 pp.

Blankespoor, B., S. Dasgupta, B. Laplante, and D. Wheeler, 2010: *The Economics of Adaptation to Extreme Weather Events in Developing Countries*. World Bank Discussion Paper No.1 in the Development and Climate Change Series, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 22 pp.

Bosello, F., R. Roson, and R.S.J. Tol, 2007: Economy wide estimates of the implications of climate change: sea level rise. *Environmental and Resource Economics*, **37**, 549-571.

Botzen, W.J.W., J.C.J.H. Aerts, and J.C.J.M. van den Bergh, 2009: Willingness of homeowners to mitigate climate risk through insurance. *Ecological Economics*, **68**, 2265-2277.

Bouwer, L.M., 2010: *Disasters and Climate Change: Analysis and Methods for Projecting Future Losses from Extreme Weather*. Ph.D. Thesis, The Institute for Environmental Studies (IVM), Vrije Universiteit, Amsterdam, Netherlands, 127 pp., ISBN 978-90-8570-596-3.

Brander, L.M., I. Bräuer, H. Gerdes, A. Ghermandi, O. Kuik, A. Markandya, S. Navrud, P.A.L.D. Nunes, M. Schaafsma H. Vos, and A. Wagtendonk, 2012: Using meta-analysis and GIS for value transfer and scaling up: valuing climate change induced losses of European wetlands. *Environmental Resource Economics*, **52**, 395-413.

Brauch, H.G., 2009a: Introduction: facing global environmental change and sectorialization of security. In: *Facing Global Environmental Change: Environmental, Human, Energy, Food, Health and Water Security Concepts* [Brauch, H.G., N.C. Behera, P. Kameri-Mbote, J. Grin, Ú. Oswald Spring, B. Chourou, C. Mesjasz, and H. Krummenacher (eds.)]. Springer, Berlin Heidelberg, Germany, pp. 27-44.

Brauch, H.G., 2009b: Securitizing global environmental change. In: *Facing Global Environmental Change: Environmental, Human, Energy, Food, Health and Water Security Concepts* [Brauch, H.G., N.C. Behera, P. Kameri-Mbote, J. Grin, Ú. Oswald Spring, B. Chourou, C. Mesjasz, and H. Krummenacher (eds.)]. Springer, Berlin Heidelberg, Germany, pp. 65-102.

Bräuninger, M., S. Butzengeiger-Geyer, A. Dlugolecki, S. Hochrainer, K. Köhler, J. Linnerooth-Bayer, R. Mechler, A. Michaelowa, and S. Schulze, 2011: *Application of Economic Instruments for Adaptation to Climate Change*. CLIMA.C.3./ETU/2010/0011, Perspectives GmbH Hamburg, Germany Office, Final Report to the

European Commission, Directorate General, CLIMA, Brussels, Belgium, 326 pp., ec.europa.eu/clima/policies/adaptation/what/docs/economic_instruments_en.pdf.

Brent, R.J., 1996: *Applied Cost-Benefit Analysis*. Edward Elgar Publishing, Ltd., Cheltenham, UK and Northampton, MA, USA, 336 pp.

Brooks, M., F. Gagnon-Lebrun, H. Harvey, C. Sauvé, and ÉcoRessources Consultants, 2009: *Prioritizing Climate Change Risks and Actions on Adaptation: A Review of Selected Institutions, Tools, and Approaches*. Final Report Prepared for the Government of Canada, Policy Research Initiative (PRI), PRI Project, Sustainable Development, PRI, Ottawa, ON, Canada, 56 pp.

Brooks, N., W.N. Adger, and M.P. Kelly, 2005: The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Global Environmental Change*, **15(2)**, 151-163.

Brouwer, R. and R. van Ek, 2004: Integrated ecological, economic and social impact assessment of alternative flood control policies in the Netherlands. *Ecological Economics*, **50 (1-2)**, 1-21, doi:16/j.ecolecon.2004.01.020.

Brown, C., W. Werick, W. Leger, and D. Fay, 2011: A decision analytic approach to managing climate risks – application to the Upper Great Lakes. *Journal of the American Water Resources Association*, **47**, 524-534.

Brown, D.J. and G. Heal, 1979: Equity, efficiency and increasing returns. *The Review of Economic Studies*, **46**, 571-585.

Bulir, A. and A.J. Hamann, 2008: Volatility of development aid: from the frying pan into the fire? *World Development*, **36(10)**, 2048-2066.

Burby, R.J., A.C. Nelson, D. Parker, and J. Handmer, 2001: Urban containment policy and exposure to natural hazards: is there a connection? *Journal of Environmental Planning and Management*, **44(4)**, 475-490.

Burby, J.R., 2006: Hurricane Katrina and the paradoxes of government disaster policy: bringing about wise governmental decisions for hazardous areas. *The ANNALS of the American Academy of Political and Social Science*, **604(1)**, 171-191.

Burby, R.J., A.B. Cigler, S.P. French, E.J. Kaiser, J. Kartez, D. Roenigk, D. Weist, and D. Whittington, 1991: *Sharing Environmental Risks: How to Control Governments' Losses in Natural Disasters.* Westview Press, Boulder, CO, USA, 280 pp.

Burton, I., 2004: Climate change and the adaptation deficit. In: *Climate Change: Building the Adaptive Capacity* [Fenech, A., D. MacIver, H. Auld, R. Bing Rong, and Y. Yin (ed.)]. Environment Canada, Meteorological Service of Canada, Gatineau, QC, Canada, pp. 25-33.

Burtraw, D., A. Krupnick, K. Palmer, A. Paul, M. Toma, and C. Bloyd, 2003: Ancillary benefits of reduced air pollution in the US from moderate greenhouse gas mitigation policies in the electricity sector. *Journal of Environmental Economics and Management*, **45**, 650-673

Butt, T.A., B.A. McCarl, and A.O. Kergna, 2006: Policies for reducing agricultural sector vulnerability to climate change in Mali. *Climate Policy*, **5**, 583-598.

Callaway, J.M., 2004: Adaptation benefits and costs: are they important in the global policy picture and how can we estimate them? *Global Environmental Change*, **14(3),** 273-282.

Callaway, J. and M. Hellmuth, 2007: *Assessing the Incremental Benefits and Costs of Coping with Development Pressure and Climate Change: A South African Case Study*. Submissions from admitted non-governmental organizations on socio-economic information under the Nairobi work programme, United Nations Framework Convention on Climate Change (UNFCCC), Geneva, Switzerland, 1 pp.

Camerer, C.F. and H. Kunreuther, 1989: Decision processes for low probability events: policy implications. *Journal of Policy Analysis and Management*, **8**, 565-592.

Carraro, C. and A. Sgobbi, 2008: *Climate Change Impacts and Adaptation Strategies in Italy: An Economic Assessment*. NOTA DI LAVORO 6.2008, Fondazione Eni Enrico Mattei, Milan, Italy, 26 pp., www.feem.it/userfiles/attach/Publication/NDL2008/NDL2008-006.pdf.

Carter, T.R., M.L. Parry, H. Harasawa, and S. Nishioka, 1994: *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations.* Part of the IPCC Special Report to the First Session of the Conference of the Parties to the UN Framework Convention on Climate Change (UNFCCC), World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), Published by the Department of Geography, University College London, London, UK and the Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Japan, with the assistance of the UK Department of the Environment and the Environment Agency of Japan, 59 pp., www.ipcc-wg3.de/special-reports/.files-images/ipcc-technical-guidelines-1994n.pdf.

Carter, T.R., R.N. Jones, X. Lu, S. Bhadwal, C. Conde, L.O. Mearns, B.C. O'Neill, M.D.A. Rounsevell, and M.B. Zurek, 2007: New assessment methods and the characterisation of future conditions. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 133-171.

Chichilnisky, G., A. Beltratti, and G. Heal, 1998: Chapter 2.1: Sustainable use of renewable resources. In: *Sustainability: Dynamics and Uncertainty* [Chichilnisky, G., G. Heal, and A. Vercelli (eds.)]. Vol. 9 of Fondazione Eni Enrico Mattei (FEEM) series on economics, energy, and environment, Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 49-76.

Chinowsky, P. and J. Price, 2013: Assessment of climate change adaptation costs for the U.S. road network. *Global Environmental Change*, **23(4)**, 764-773.

Chishakwe, N., L. Murray, and M. Chambwera, 2012: *Building Climate Change Adaptation on Community Experiences: Lessons from Community-Based Natural Resource Management in Southern Africa*. International Institute for Environment and Development (IIED), London, UK, 126 pp.

Chopra, K., 2005: *Ecosystems and Human Well-Being*: *Policy Responses, Volume 3*. Island Press, Washington, DC, USA, 621 pp.

Christiansen, L., A. Olhoff, and S. Traerup, 2011: *Technologies for Adaptation: Perspectives and Practical Experiences*. UNEP Risø Centre on Energy, Climate and Sustainable Development, Roskilde, Denmark, 123 pp.

Cimato, F. and M. Mullan, 2010: *Adapting to Climate Change: Analysing the Role of Government*. DEFRA Evidence and Analysis Series Paper 1, Department for Environment, Food and Rural Affairs (DEFRA), London, UK, 79 pp.

Claassen, R., A. Cattaneo, and R. Johansson, 2008: Cost-effective design of agri-environmental payment programs: U.S. experience in theory and practice. *Ecological Economics*, **65**, 737-752.

CMEPSP, 2009: *Report of the Commission on the Measurement of Economic Performance and Social Progress*. The Commission on the Measurement of Economic Performance and Social Progress (CMEPSP), Paris, France, 291 pp.

Coase, R.H., 1937: The nature of the firm. *Economica*, **4**, 386-405.

Coase, R.H., 1960: The problem of social cost. *Journal of Law and Economics*, **3**, 1-44.

Cohen, M. and J. Sebstad, 2003: *Reducing Vulnerability: The Demand for Micro-insurance*. An Initiative of Austria/CGAP/DFID/UNDP, MicroSave-Africa, Nairobi, Kenya, 61 pp.

Cohen, M. and J. Sebstad, 2005: Reducing vulnerability: the demand for micro-insurance. *Journal of International Development*, **17(3)**, 397-474.

Comim, F., 2008: Climate injustice and development: a capability perspective. *Development*, **51**, 344-349.

Collier, B., J. Skees, and B. Barnett, 2009: Weather index insurance and climate change: opportunities and challenges in lower income countries. *The Geneva Papers*, **34(3)**, 401-424, doi:10.1057/gpp.2009.11.

Dalby, S., 2009: *Security and Environmental Change*. Polity Press, Cambridge, UK and Malden, MA, USA, 197 pp.

DCLG, 2009: *Multi-Criteria Analysis: A Manual*. UK Department for Communities and Local Government (DCLG), Communities and Local Government Publications, Wetherby, West Yorkshire, UK, 165 pp.

de Bruin, K., 2011: *An Economic Analysis of Adaptation to Climate Change Under Uncertainty*. Ph.D. Thesis, Wageningen University, Wageningen, Netherlands, 179 pp.

de Bruin, K., R.B. Dellink, A. Ruijs, L. Bolwidt, A. Van Buuren, J. Graveland, R.S. De Groot, P.J. Kuikman, S. Reinhard, R.P. Roetter, V.C. Tassone, A. Verhagen, and E.C. van Ierland, 2009a: Adapting to climate change in The Netherlands: an inventory of climate adaptation options and ranking of alternatives. *Climatic Change*, **95 (1)**, 23-45.

de Bruin, K.C., R.B. Dellink, and R.S.J. Tol, 2009b: AD-DICE: an implementation of adaptation in the DICE model. *Climatic Change*, **95 (1-2)**, 63-81.

de Bekker-Grob, E.W., M. Ryan, and K. Gerard, 2012: Discrete choice experiments in health economics: a review of the literature. *Health Economics*, **21(2)**, 145-172.

DeCanio, S.J., 2007: *Reflections on Climate Change, Economic Development, and Global Equity*. Presented at the 2007 Leontief Prize Ceremony, Tufts University, Global Development and Environment Institute, October 17, 2007, 19 pp., www.ase.tufts.edu/gdae/about_us/leontief/DeCanioLeontief07.pdf.

De Lucena, A.F.P., R. Schaeffer, and A.S. Szklo, 2010: Least-cost adaptation options for global climate change impacts on the Brazilian electric power system. *Global Environmental Change*, **20(2)** 342-350.

Dellink, R., M. den Elzen, H. Aiking, E. Bergsma, F. Berkhout, T. Dekker, and J. Gupta, 2009: Sharing the burden of financing adaptation to climate change. *Global Environmental Change*, **19(4)**, 411-421.

Delmer, D.P., C. Nottenburg, G.D. Graff, and A.B. Bennett, 2003: Intellectual property resources for international development in agriculture. *Plant Physiology*, **133(4)**, 1666-1670.

Deschenes, O. and M. Greenstone, 2007: The economic impacts of climate change: evidence from agricultural output and random fluctuations in weather. *American Economic Review*, **97**, 354-385.

Dessai, S., 2003: Heat stress and mortality in Lisbon part II. An assessment of the potential impacts of climate change. *International Journal of Biometeorology*, **48(1)**, 37-44.

Dessai , S. and M. Hulme, 2007: Assessing the robustness of adaptation decisions to climate change uncertainties: a case study on water resources management in the East of England. *Global Environmental Change*, **17**, 59-72.

Dessai, S., M. Hulme, R. Lempert, and R. Pielke, Jr., 2009a: Climate prediction: a limit to adaptation? In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, W.N., I. Lorenzoni, and K.L. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK, pp. 64-78.

Dessai, S., M. Hulme, R. Lempert, and R. Pielke, Jr., 2009b: Do we need better predictions to adapt to a changing climate? *Eos*, **90(13)**, 111-112.

Dietz, S., C. Hope, and N. Patmore, 2009: Some economics of "dangerous" climate change: reflections on the *Stern Review*. *Global Environmental Change*, **17(3-4)**, 311-325.

Dobbs, T.L. and J. Pretty, 2008: Case study of agri-environmental payments: the United Kingdom. *Ecological Economics*, **65**, 765-775.

Dobes, L. and J. Bennett, 2009: Multi-criteria analysis: "good enough" for government work? *Agenda*, **16(3)**, 7-30.

Dutz, M.A. and S. Sharma, 2102: *Green Growth, Technology and Innovation*. Policy Research Working Paper 5932, the Economic Policy and Debt Department, Poverty Reduction and Economic Management, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 45 pp.

Easterling, W.E., P.R. Crosson, N.J. Rosenberg, M.S. McKenney, L.A. Katz, and K.M. Lemon, 1993: Paper 2. Agricultural impacts of and responses to climate change in the Missouri-Iowa-Nebraska-Kansas (MINK) region. *Climatic Change*, **24(1-2)**, 23-61.

Ebi, K.L., 2008: Adaptation costs for climate change-related cases of diarrhoeal disease, malnutrition, and malaria in 2030. *Global Health*, **4**, 9, doi:10.1186/1744-8603-4-9.

Ebi, K.L. and I. Burton, 2008: Identifying practical adaptation options: an approach to address climate change-related health risks. *Environmental Science & Policy*, **11(4)**, 359-369.

ECA, 2009: *Shaping Climate-Resilient Development: A Framework for Decision-Making*. A Report of the Economics of Climate Adaptation Working Group, Economics of Climate Adaptation (ECA), a partnership of the ClimateWorks Foundation, Global Environment Facility (GEF), European Commission (EC), McKinsey & Company, The Rockefeller Foundation, Standard Chartered Bank, and Swiss Re, 159 pp.

Egbendewe-Mondzozo, A., M. Musumba, B.A. McCarl, and X.M. Wu, 2011: Climate change and vector-borne diseases: an economic impact analysis of malaria in Africa. *International Journal of Environmental Research and Public Health*, **8(3)**, 913-930.

Eisenack, K., 2013: The inefficiency of private adaptation to pollution in the presence of endogenous market structure. *Environmental and Resource Economics* (in press), doi:10.1007/s10640-013-9667-6.

Elbehri, A., A. Genest, and M. Burfisher, 2011: *Global Action on Climate Change in Agriculture: Linkages to Food Security, Markets and Trade Policies in Developing Countries.* Trade and Markets Division, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 82 pp.

Elsasser, H. and R. Bürki, 2002: Climate change as a threat to tourism in the Alps. *Climate Research*, **20**, 253-257.

Engel, S. and C. Palmer, 2008: Payments for environmental services as an alternative to logging under weak property rights: the case of Indonesia. *Ecological Economics*, **65**, 799-809.

Engel, S., S. Pagiola, and S. Wunder, 2008: Designing payments for environmental services in theory and practice: an overview of the issues. *Ecological Economics*, **65**, 663-674.

Eriksen, S., P. Aldunce, C.S. Bahinipati, R. Martins, J.I. Molefe, C. Nhemachena, K. O'Brien, F. Olorunfemi, J. Park, L. Sygna, and K. Ulsrud, 2011: When not every response to climate change is a good one: identifying principles for sustainable adaptation. *Climate and Development*, **3(1)**, 7-20.

ESMAP, 2010: *Climate Impacts on Energy Systems: Key Issues for Energy Sector Adaptation*. Energy Sector Management Assistance Program (ESMAP) Studies and The World Bank, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 178 pp.

European Environmental Agency, 2007: *Climate Change: The Cost of Inaction and the Cost of Adaptation*. EEA Technical Report No. 13/2007, European Environmental Agency (EEA), Office for Official Publications of the European Communities, Luxembourg, Luxembourg, 67 pp.

Fankhauser, S., 1995: Protection versus retreat: the economic costs of sea-level rise. *Environment and Planning A*, **27(2)**, 299-319.

Fankhauser, S., 2010: The costs of adaptation. *Wiley Interdisciplinary Review Climate Change*, **1(1)**, 23-30.

Fankhauser, S. and R. Soare, 2013: An economic approach to adaptation: illustrations from Europe. *Climatic Change*, **118**, 367-379.

Fankhauser, S. and R.S.J. Tol, 2005: On climate change and economic growth. *Resource and Energy Economics*, **27(1)**, 1-17.

Fankhauser, S., J.B. Smith, and R.S.J. Tol, 1999: Weathering climate change: some simple rules to guide adaptation decisions. *Ecological Economics*, **30(1)**, 67-78.

Farber, D., 2007: Basic compensation for victims of climate change. *University of Pennsylvania Law Review*, **155(6)**, 1605-1656.

Finger, R., W. Hediger, and S. Schmid, 2011: Irrigation as adaptation strategy to climate change – a biophysical and economic appraisal for Swiss maize production. *Climatic Change*, **105(3-4)**, 509-528.

Fischhoff, B., P. Slovic, S. Lichtenstein, S. Read, and B. Combs, 1978: How safe is safe enough? A psychometric study of attitudes towards technological risks and benefits. *Policy Sciences*, **9(2)**, 127-152.

Ford, J.D., T. Pearce, J. Prno, F. Duerden, L.B. Ford, T.R. Smith, and M. Beaumier, 2011: Canary in a coal mine: perceptions of climate change risks and response options among Canadian mine operations. *Climatic Change*, **109(3-4)**, 399-415.

Freeman, M., 2003: *The Measurement of Environmental and Resource Values: Theory and Methods*. 2nd edn., Resources for the Future, Washington, DC, USA, 491 pp.

Friedman, M., 1953: *Essays in Positive Economics*. University of Chicago Press, Chicago, IL, USA, 328 pp.

Frihy, O.E., 2001: The necessity of environmental impact assessment (EIA) in implementing coastal projects: lessons learned from the Egyptian Mediterranean Coast. *Ocean & Coastal Management*, **44(7-8)**, 489-516.

Frost, P.G.H. and I. Bond, 2008: The CAMPFIRE programme in Zimbabwe: payments for wildlife services. *Ecological Economics*, **65(4)**, 776-787.

Froyn, C.B., 2005: Decision criteria, scientific uncertainty, and the global warming controversy. *Mitigation and Adaptation Strategies for Global Change*, **10(2)**, 183-211.

Füssel, H.-M., 2007: Adaptation planning for climate change: concepts, assessment approaches, and key lessons. *Sustainability Science*, **2(2)**, 265-275.

Füssel, H.-M., 2009: *Review and Quantitative Analysis of Indices of Climate Change Exposure, Adaptive Capacity, Sensitivity, and Impacts*. Background note to the World Development Report 2010, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 34 pp.

Füssel, H.-M., 2010: How inequitable is the global distribution of responsibility, capability, and vulnerability to climate change: a comprehensive indicator-based assessment. *Global Environmental Change*, **20(4)**, 597-611, doi:10.1016/j.gloenvcha.2010.07.009.

Füssel, H.-M., 2011: Ethics and international adaptation funding (review essay). *Carbon & Climate Law Review*, **5(2)**, 295-299.

Füssel, H.-M., S. Hallegatte, and M. Reder, 2012: International adaptation funding. In: *Climate Change, Justice and Sustainability: Linking Climate and Development Policy* [Edenhofer, O., J. Wallacher, H. Lotze-Campen, M. Reder, B. Knopf, and J. Müller (eds.)]. Springer, Dordrecht, Netherlands, pp. 311-330.

Gawel, E., C. Heuson, and P. Lehmann, 2012: *Efficient Public Adaptation to Climate Change: An Investigation of Drivers and Barriers from a Public Choice Perspective*. UFZ Discussion Paper No. 14/2012, Helmholtz-Zentrum für Umweltforschung GmbH – UFZ, Leipzig, Germany, 27 pp.

Gibson, C.C., K. Andersson, E. Ostrom, and S. Shivakumar, 2005: *The Samaritan's Dilemma: The Political Economy of Development Aid*. Oxford University Press, New York, NY, USA, 264 pp.

Gilboa, I., 2010: *Making Better Decisions: Decision Theory in Practice*. Wiley-Blackwell, Chichester, UK, 232 pp.

Giordano, T., 2012: Adaptive planning for climate change resilient long-lived infrastructures. *Utilities Policy*, **23**, 80-89.

Goodess, C.M., J.W. Hall, M. Best, R. Betts, L. Cabantous, P.D. Jones, C.G. Kilsby, A. Pearman, and C.J. Wallace, 2007: Climate scenarios and decision making under uncertainty. *Built Environment*, **33(1)**, 10-30.

Goulden, M., D. Conway, and A. Persechino, 2009: Adaptation to climate change in international river basins in Africa: a review/Adaptation au changement climatique dans les bassins fluviaux internationaux en Afrique: une revue. *Hydrological Sciences Journal*, **54(5)**, 805-828.

Grafakos, S., 2012: Participatory integrated assessment of flood protection measures for climate adaptation in Dhaka. *Environment and Urbanization*, **24(1)**, 197-213, doi:10.1177/0956247811433538.

Graff, G.D., S.E. Cullen, K.J. Bradford, D. Zilberman, and A.B. Bennett, 2003: The public-private structure of intellectual property ownership in agricultural biotechnology. *Nature Biotechnology*, **21(9)**, 989-995.

Grasso, M., 2010: *Justice in Funding Adaptation under the International Climate Change Regime*. Springer Science, Dordrecht, Netherlands, 184 pp.

Griffin, R.C., 2012: The origins and ideals of water resource economics in the U.S. *Annual Reviews of Resource Economics*, **4**, 353-377, doi:10.1146/annurev-resource-110811-114517.

Grothmann, T. and A. Patt, 2005: Adaptive capacity and human cognition: the process of individual adaptation to climate change. *Global Environmental Change*, **15**, 199-213.

Groves, D.G. and R.J. Lempert, 2007: A new analytic method for finding policy-relevant scenarios. *Global Environmental Change*, **17**, 73-85.

Groves, D.G., D. Knopman, R. Lempert, S. Berry, and L. Wainfan, 2007: *Presenting Uncertainty About Climate Change to Water Resource Managers – Summary of Workshops with the Inland Empire Utilities Agency*. Rand Corporation Technical Report describing research sponsored by the National Science Foundation and conducted under the auspices of the Environment, Energy, and Economic Development Program (EEED) within RAND Infrastructure, Safety, and Environment (ISE), RAND Corporation, Santa Monica, CA, USA, 80 pp.

Groves, D.G., M. Davis, R. Wilkinson, and R. Lempert, 2008: Planning for climate change in the Inland Empire: Southern California. *Water Resources IMPACT*, **10(4)**, 14-17.

Guesnerie, R., 2004: Calcul économique and développment durable. *Revue économique*, **55**, 363-382.

Gupta, S., D. Tirpak, N. Burger, J. Gupta, N. Höhne, A. Boncheva, G. Kanoan, C. Kolstad, J. Kruger, A. Michaelowa, S. Murase, J. Pershing, T. Saijo, and A. Sari, 2007: Policies, instruments and co-operative arrangements. In: *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Metz, B., O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer (eds)]. Cambridge University Press, Cambridge, UK and New York, NY USA, pp. 746-807.

Hall, J.W., 2007: Probabilistic climate scenarios may misrepresent uncertainty and lead to bad adaptation decisions. *Hydrological Processes*, **21(8)**, 1127-1129.

Hallegatte, S., 2006: *A Cost-Benefit Analysis of the New Orleans Flood Protection System*. Regulatory Analysis 06-02, The AEI-Brookings Joint Center for Regulatory Studies, Washington, DC, USA, 18 pp.

Hallegatte, S., 2008: An adaptive regional input-output model and its application to the assessment of the economic cost of Katrina. *Risk Analysis*, **28(3)**, 779-799.

Hallegatte, S., 2009: Strategies to adapt to an uncertain climate change. *Global Environmental Change*, **19**, 240-247.

Hallegatte, S., 2012: *An Exploration of the Link between Development, Economic Growth, and Natural Risk*. Policy Research Working Paper No. 6216, Office of the Chief Economist, Sustainable Development Network, Prepared as a background paper to the World Development Report 2014, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 32 pp.

Hallegatte, S. and P. Dumas, 2009: Can natural disasters have positive consequences? Investigating the role of embodied technical change. *Ecological Economics*, **68**, 777-786.

Hallegatte, S., J.C. Hourcade, and P. Dumas, 2007: Why economic dynamics matter in assessing climate change damages: illustration on extreme events. *Ecological Economics*, **62**, 330-340.

Hallegatte, S., F. Lecocq, and C. De Perthuis, 2011a: *Designing Climate Change Adaptation Policies – An Economic Framework*. Policy Research Working Paper No. 5568, Office of the Chief Economist, Sustainable Development Network, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 39 pp.

Hallegatte, S., V. Przyluski, and A. Vogt-Schilb, 2011b: Building world narratives for climate change impact, adaptation and vulnerability analyses. *Nature Climate Change*, **1**, 151-155.

Hallegatte, S., A. Shah, C. Brown, R. Lempert, and S. Gill, 2012: *Investment Decision Making under Deep Uncertainty – Application to Climate Change*. Policy Research Working Paper No. 6193, Office of the Chief Economist, Sustainable Development Network, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 39 pp.

Handmer, J., Y. Honda, Z. Kundzewicz, N. Arnell, G. Benito, J. Hatfield, I. Mohamed, P. Peduzzi, S. Wu, B. Sherstyukov, K. Takahashi, and Z. Yan, 2012: Changes in impacts of climate extremes: human systems and ecosystems. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (ed.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 231-290.

Hansen, L.P. and T.J. Sargent, 2008: *Robustness*. Princeton University Press, Princeton, NJ, USA, 435 pp.

Hanson, S., R. Nicholls, N. Ranger, S. Hallegatte, J. Corfee-Morlot, C. Herweijer, and J. Chateau, 2011: A global ranking of port cities with high exposure to climate extremes. *Climatic Change*, **104**, 89-111.

Harberger, A.C., 1978: On the use of distributional weights in social cost-benefit analysis. *Journal of Political Economy*, **86 (2 Pt. 2)**, S87-S120.

Harberger, A.C., 1984: Basic needs versus distributional weights in social cost-benefit analysis. *Economic Development and Cultural Change*, **32(3)**, 455-474.

Harris, P.G., 2010: *World Ethics and Climate Change: From International to Global Justice*. Edinburgh Studies in World Ethics, Edinburgh University Press, Edinburgh, UK, 214 pp.

Hassan, E., O. Yaqub, and S. Diepeveen, 2010: *Intellectual Properties and Developing Countries: A Review of the Literature*. Technical Report prepared for the UK Intellectual Property Office and the UK Department for International Development, Rand Europe, Cambridge, UK, 70 pp., www.rand.org/content/dam/rand/pubs/technical_reports/2010/RAND_TR804.pdf.

Heal, G., 2009: Climate economics: a meta-review and some suggestions for future research. *Review of Environmental Economics and Policy*, **3(1)**, 4-21.

Heal, G., 2012: Reflections – defining and measuring sustainability. *Review of Environmental Economics and Policy*, **6(1)**, 147-163.

Heal, G. and B. Kriström, 2001: National income and the environment. Paper prepared for inclusion in the *Handbook of Environmental Economics*, doi.org/10.2139/ssrn.279112.

Heal, G. and B. Kriström, 2002: Uncertainty and climate change. *Environmental and Resource Economics*, **22**, 3-39.

Heltberg, R., P.B. Siegel, and S.L. Jorgensen, 2009: Addressing human vulnerability to climate change: toward a 'no-regrets' approach. *Global Environmental Change*, **19**, 89-99.

Henriet, F., S. Hallegatte, and L. Tabourier, 2011: Firm-network characteristics and economic robustness to natural disasters. *Journal of Economic Dynamics and Control*, **36**, 150-167.

Henry, C., 1974: Option values in the economics of irreplaceable assets. *The Review of Economic Studies*, **41**, 89-104.

Henry, C. and M. Henry, 2002: *Formalization and Applications of the Precautionary Principles*. Columbia University Department of Economics Discussion Paper Series No. 0102-22, 19 pp., doi.org/10.2139/ssrn.1084972.

Henry, C. and J.E. Stiglitz, 2010: Intellectual property, dissemination of innovation and sustainable development. *Global Policy*, **1(3)**, 237-251.

Hertel, T.W., A.A. Golub, A.D. Jones, M. O'Hare, R.J. Plevin, and D.M. Kammen, 2010: Effects of US maize ethanol on global land use and greenhouse gas emissions: estimating market-mediated responses. *BioScience*, **60(3)**, 223-231.

Hertzler, G., 2007: Adapting to climate change and managing climate risks by using real options. *Australian Journal of Agricultural Research*, **58**, 985-992.

Hess, U. and J. Syroka, 2005: *Weather-Based Insurance in Southern Africa: The Case of Malawi*. Agriculture and Rural Development (ARD) Discussion Paper 13, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 67 pp.

Heyward, M., 2007: Equity and international climate change negotiations: a matter of perspective. *Climate Policy*, **7**, 518-534.

Hochrainer, S. and R. Mechler, 2011: Natural disaster risk in Asian megacities – a case for risk pooling? *Cities*, **28**, 53-61.

Hochrainer, S., R. Mechler, and G. Pflug, 2009: Climate change and financial adaptation in Africa. Investigating the impact of climate change on the robustness of index-based microinsurance in Malawi. *Mitigation and Adaptation Strategies for Global Change*, **14**, 231-250, doi:10.1007/s11027-008-9162-5.

Hof, A.F., K.C. de Bruin, R.B. Dellink, M.G.J. den Elzen, and D.P. van Vuuren, 2009: The effect of different mitigation strategies on international financing of adaptation. *Environmental Science and Policy*, **12 (7)**, 832-843.

Hof, A.F., D.P. van Vuuren, and M.G.J. den Elzen, 2010: A qualitative minimax regret approach to climate change: does discounting still matter? *Ecological Economics*, **70(1)**, 43-51.

Hogarth, R. and H. Kunreuther, 1995: Decision making under ignorance: arguing with yourself. *Journal of Risk and Uncertainty*, **10**, 15-36.

Höppe, P. and E. Gurenko, 2006: Scientific and economic rationales for innovative climate insurance solutions. *Climate Policy*, **6(6)**, 607-620.

Hourcade, J.C., P. Ambrosi, and P. Dumas, 2009: Beyond the Stern Review: lessons from a risky venture at the limits of the cost-benefit analysis. *Ecological Economics*, **68 (10)**, 2479-2484.

Hudgens, D. and A. Jones, 2010: *Application of Ecological and Economic Models of the Impacts of Sea-Level Rise to the Delaware Estuary*. Report by Industrial Economics, Incorporated (IEc), Prepared for the U.S. Environmental Protection Agency, Climate Change Division, Climate Science Impacts Branch and Partnership for the Delaware Estuary, IEc, Cambridge, MA, USA, 48 pp., www.delawareestuary.org/pdf/Climate/IEc-%20Delaware%20Estuary%20SLAMM%20HEA%20-%20June%202010.pdf.

Hughes, G., P. Chinowsky, and K. Strzepak, 2010: The costs of adaptation to climate change for water infrastructure in OECD countries. *Utility Policy*, **18(3)**, 142-153.

Hunt, A. and T. Taylor, 2009: Values and cost-benefit analysis: economic efficiency in adaptation. In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, W.N., I. Lorenzoni, and K.L. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK, pp. 197-211.

Hunt, A. and P. Watkiss, 2011: Climate change impacts and adaption in cities: a review of the literature. *Climatic Change*, **104(1)**, 13-49, doi:10.1007/s10584-010-9975-6.

Hurwicz, L., 1951: Some specification problems and application to econometric models. *Econometrica*, **19**, 343-344.

Iglesias, A., S. Quiroga, and A. Diz, 2011: Looking into the future of agriculture in a changing climate. *European Review of Agricultural Economics*, **38(3)**, 427-447.

IIASA, 2012: *Global Energy Assessment – Toward a Sustainable Future.* International Institute for Applied Systems Analysis (IIASA), Cambridge University Press, Cambridge, UK and New York, NY, USA, 1882 pp.

IMF, 2008: *The Fiscal Implications of Climate Change*. Fiscal Affairs Department, International Monetary Fund (IMF), Washington, DC, USA, 49 pp.

Inthorn, J., L. Kaelin, and M. Reder, 2010: *Gesundheit und Gerechtigkeit. Ein interkultureller Vergleich zwischen Österreich und den Philippinen*. Schriftenreihe Ethik und Recht in der Medizin, Springer-Verlag, Wien, Österreich, and New York, NY, USA, 182 pp.

IPCC, 2012: Summary for Policymakers. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1-19.

Jacoby, H., M. Rabassa, and E. Skoufias, 2011: *Distributional Implications of Climate Change in India*. Policy Research Working Paper No. 5623, Poverty Reduction and Equity Unit, Poverty Reduction and Economic Management Network, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 56 pp.

Jagers, S.C. and G. Duus-Otterström, 2008: Dual climate change responsibility: on moral divergences between mitigation and adaptation. *Environmental Politics*, **17**, 576-591.

James, O., 2000: Regulation inside government: public interest justifications and regulatory failures. *Public Administration*, **78(2)**, 327-334.

Janssen, R. and M. Van Herwijnen, 2006: A toolbox for multicriteria decision-making. *International Journal of Environmental Technology and Management*, **6(1)**, 20-39.

Johnson, E.J. and G. Daniel, 2003: Do defaults save lives? *Science*, **302(5649)**, 1338-1339.

Julius, S.H. and J.D Scheraga, 2000: The TEAM model for evaluating alternative adaptation strategies. In: *Research and Practice in Multiple Criteria Decision Making: Proceedings of the XIVth International Conference on Multiple Criteria Decision Making (MCDM), Charlottesville, VA, USA, June 8-12, 1998* [Haimes, Y.Y. and R.E. Steuer (eds.)]. Part II, Vol. 487, Lecture Notes in Economics and Mathematical Systems, Springer-Verlag, Berlin Heidelberg, Germany, pp. 319-330.

Kanbur, R., 2010: Macro crises and targeting transfers to the poor. In: *Globalization and Growth: Implications for a Post-Crisis World* [Spence, M. and D. Leipziger (eds.)]. The Commission on Growth and Development, The World Bank Group, Washington, DC, USA, pp. 109-122.

Keeney, R.L. and H. Raiffa, 1993: *Decisions with Multiple Objectives: Preferences and Value Tradeoffs*. Cambridge University Press, Cambridge, UK, 569 pp.

Kelly, D.L., C.D. Kolstad, and G.T. Mitchell, 2005: Adjustment costs from environmental change. *Journal of Environmental Economics and Management*, **50(3)**, 468-495.

Kemfert, C., 2002: An integrated assessment model of Economy-Energy-Climate – The Model Wiagem. *Integrated Assessment Journal*, **6(1)**, 75-82.

Kemfert, C., 2007: Klimawandel kostet die deutsche Volkswirtschaft Milliarden. In: *Wochenbericht*. Nr. 11/2007, 74, Jahrgang/14, März 2007, Das Deutsche Institut für Wirtschaftsforschung (DIW), DIW, Berlin, Germany, pp 165-169.

Khan, S., M.A. Khan, M.A. Hanjrab, and J. Mu, 2009: Pathways to reduce the environmental footprints of water and energy inputs in food production. *Food Policy*, **34(2)**, 141-149.

Kiker, G.A., T.S. Bridges, A. Varghese, T.P. Seager, and I. Linkov. 2005: Application of multicriteria decision analysis in environmental decision making. *Integrated Environmental Assessment and Management*, **1(2)**, 95-108.

King, J.R., 2005: *Report of the Study Group on Fisheries and Ecosystem Responses to Recent Regime Shifts*. PICES Scientific Report 28, Institute of Ocean Sciences, Secretariat, North Pacific Marine Science Organization (PICES), Sidney, BC, Canada, 162 pp.

Kirshen, P., M. McCluskey, R. Vogel, and K. Strzepek, 2005: Global analysis of changes in water supply yields and costs under climate change: a case study in China. *Climatic Change*, **68(3)**, 303-330, doi:10.1007/s10584-005-1148-7.

Klein, R.J.T., 2009: Identifying countries that are particularly vulnerable to the adverse effects of climate change: an academic or a political challenge? *Carbon and Climate Law Review*, **3**, 284-291.

Klein, R.J.T. and Å. Persson, 2008: Financing adaptation to climate change: issues and priorities. In: *Climate Change, European Climate Platform Reports.* European Climate Platform (ECP) Report No. 8, Research carried out in the projects ADAM (Adaptation and Mitigation Strategies: Supporting European Climate Policy) and Clipore (Climate Policy Research), The Centre for European Policy Studies (CEPS), Brussels, Belgium, 18 pp., www.ceps.eu/node/1569.

Klein, R.J.T., E.L.F. Schipper, and S. Dessai, 2005: Integrating mitigation and adaptation into climate and development policy: three research questions. *Environmental Science & Policy*, **8**, 579-588.

Klinsky, S. and H. Dowlatabadi, 2009: Conceptualizations of justice in climate policy. *Climate Policy*, **9**, 88-108.

Koetse, M. and P. Rietveld, 2012: Adaptation to climate change in the transport sector. *Transport Reviews*, **32(3)**, 267-286.

Kok, M. and H. De Coninck, 2007: Widening the scope of policies to address climate change: directions for mainstreaming. *Environmental Science & Policy*, **10**, 587-599.

Koleva, N.G., U.A. Schneider, and B.A. McCarl, 2011: Pesticide and greenhouse gas externalities from US agriculture – the impact of their internalization and climate change. *Climate Change Economics*, **4(3)**, 1350008, doi:10.1142/S2010007813500085.

Korteling, B., S. Dessai, and Z. Kapelan, 2013: Using information-gap decision theory for water resources planning under severe uncertainty. *Water Resources Management*, **27**, 1149-1172.

Kostandini, G., B.F. Mills, S.W. Omamo, and S. Wood, 2009: *Ex ante* analysis of the benefits of transgenic drought tolerance research on cereal crops in low-income countries. *Agricultural Economics*, **40(4)**, 477-492.

Krantz, D. and H. Kunreuther, 2007: Goals and plans in decision-making. *Judgment and Decision Making*, **2**, 137-168.

Kreeger, D., J. Adkins, P. Cole, R. Najjar, D. Velinsky, P. Conolly, and J. Kraeuter, 2010: *Climate Change and the Delaware Estuary: Three Case Studies in Vulnerability Assessment and Adaptation Planning*. PDE Report No. 10-01, Partnership for the Delaware Estuary, Wilmington, DE, USA, 118 pp., delawareestuary.org/pdf/Climate/Climate%20Change%20and%20the%20Delaware%20Estuary_PDE-10-01.pdf.

Krueger, A.O., 1990: Government failures in development. *Journal of Economic Perspectives*, **4 (3)**, 9-23.

Kubal, C., D. Haase, V. Meyer, and S. Scheuer, 2009: Integrated urban flood risk assessment – adapting a multicriteria approach to a city. *Natural Hazards and Earth System Sciences*, **9(6)**, 1881-1895.

Kunreuther, H., 2008: Moral hazard. In: *Encyclopedia of Quantitative Risk Assessment* [Melnick, E.L. and B.S. Everitt (eds.)]. John Wiley & Sons, Chichester, UK, doi:10.1002/9780470061596.risk0655.

Kunreuther, H. and R. Roth, 1998: *Paying the Price: The Status and Role of Insurance Against Natural Disasters in the United States*. 1st edn., Joseph Henry Press, Washington, DC, USA, 320 pp.

Kunreuther, H., R. Ginsberg, L. Miller, P. Sagi, P. Slovic, B. Borkan, and N. Katz, 1978: *Disaster Insurance Protection: Public Policy Lessons*. John Wiley & Sons Canada, Ltd., Mississauga, ON, Canada, 400 pp.

Kunreuther, H., R. Meyer, and E. Michel-Kerjan, 2009: Overcoming decision biases to reduce losses from natural catastrophes. In: *The Behavioral Foundations of Public Policy* [Shafir, E. (ed.)]. Princeton University Press, Princeton, NJ, USA and Woodstock, UK, pp. 398-414.

Kunreuther, H., G. Heal, M. Allen, O. Edenhofer, C.B. Field, and G. Yohe, 2013: Risk management and climate change. *Nature Climate Change*, **3**, 447-450.

Laffont, J.J., 1995: Regulation, moral hazard and insurance of environmental risks. *Journal of Public Economics*, **58(3)**, 319-336.

Lall S.V. and U. Deichmann, 2010: *Density and Disasters: Economics of Urban Hazard Risk*. Policy Research Working Paper 5161, the Finance, Economics, and Urban Development Department and the Environment and Energy Team, Development Research Group, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 48 pp.

Larsen, P.H., S. Goldsmith, O. Smith, M.L. Wilson, K. Strzepek, P. Chinowsky, and B. Saylor, 2008: Estimating future costs for Alaska public infrastructure at risk from climate change. *Global Environmental Change*, **18(3)**, 442-457.

Layton, D. and G. Brown, 2000: Heterogeneous preferences regarding global climate change. *The Review of Economics and Statistics*, **82(4)**, 616-624.

Leary, N., J. Adejuwon, V. Barros, I. Burton, J. Kukarni, and R. Lasco (eds.), 2008: *Climate Change and Adaptation*. Earthscan, London, UK and Sterling, VA, USA, 381 pp.

Lecocq, F. and Z. Shalizi, 2007: *Balancing Expenditures on Mitigation of and Adaptation to Climate Change: An Exploration of Issues Relevant to Developing Countries*. Policy Research Working Paper No. 4299, the Sustainable Rural and Urban Development Team, Development Research Group, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 48 pp.

Lemieux, C.J., and D.J. Scott, 2005: Climate change, biodiversity conservation and protected area planning in Canada. *Canadian Geographer / Le Géographecanadien*, **49(4)**, 384-397.

Lempert, R.J. and M.T. Collins, 2007: Managing the risk of uncertain thresholds responses: comparison of robust, optimum, and precautionary approaches. *Risk Analysis*, **27**, 1009-1026.

Lempert, R. and D.G. Groves, 2010: Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west. *Technological Forecasting and Social Change*, **77**, 960-974.

Lempert, R. and N. Kalra, 2009: *Managing Climate Risks in Developing Countries with Robust Decision Making*. World Resources Report, World Resources Institute (WRI), Washington, DC, USA.

Lempert, R.J. and N. Kalra, 2011: *Managing Climate Risks in Developing Countries with Robust Decision Making*. World Resources Institute (WRI) Report, Washington, DC, USA, 9 pp., www.wri.org/sites/default/files/uploads/wrr_lempert_and_kalra_uncertainty_.pdf.

Lempert, R.J. and M.E. Schlesinger, 2000: Robust strategies for abating climate change. *Climatic Change*, **45(3-4)**, 387-401.

Lempert, R.J., D.G. Groves, S.W. Popper, and S.C. Bankes, 2006: A general, analytic method for generating robust strategies and narrative scenarios. *Management Science*, **52(4)**, 514-528.

Lempert, R., N. Kalra, S. Peyraud, Z. Mao, S.B. Tan, D. Cira, and A. Lotsch, 2013: *Ensuring Robust Flood Risk Management in Ho Chi Minh City*. Policy Research Working Paper No. 6465, the Office of the Chief Economist, Sustainable Development Network, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 63 pp.

Lesser, W., 2007: Chapter 4.5: Plant breeders' rights: an introduction. In: *Intellectual Property Management in Health and Agricultural Innovations: A Handbook of Best Practices* [Krattiger, A., R.T. Mahoney, L. Nelsen, J.A. Thomson, A.B. Bennett, K. Satyanarayana, G.D. Graff, C. Fernandez, and S.P. Kowalski (eds.)]. Vol. 2, Centre for the Management of Intellectual Property in Health Research and Development (MIHR), Oxford Centre for Innovation, Oxford, UK and Public Intellectual Property Resource for Agriculture (PIPRA), Davis, CA, USA, pp. 381-388.

Létard, V., H. Flandre, S. Lepeltier, 2004: *La France et les Français Face à la Canicule: les Leçons d'une Crise*. Rapport d'information du Sénat no 195, Session Ordinaire de 2003-2004, Annexe au procès-verbal de la séance du 3 février 2004, 391 pp., www.senat.fr/rap/r03-195/r03-1951.pdf (in French).

Levine, M.E. and J.L. Forrence, 1990: Regulatory capture, public interest, and the public agenda: toward a synthesis. *Journal of Law, Economics, & Organization*, **6**, 167-198.

Lichtenberg, E. and R. Smith-Ramírez, 2011: Slippage in conservation cost sharing. *American Journal of Agricultural Economics*, **93(1)**, 113-129.

Linnerooth-Bayer, J., R. Mechler, and G. Pflug, 2005: Refocusing disaster aid. *Science*, **309**, 1044-1046.

Linnerooth-Bayer, J., S. Hochrainer, and R. Mechler, 2011: Insurance against losses from natural disasters in developing countries: evidence, gaps and the way forward. *Journal of Integrated Disaster Risk Management*, **1(1)**, doi:10.5595/idrim.2011.0013.

Linquiti, P. and N. Vonortas, 2012: The value of flexibility in adapting to climate change: a real options analysis of investments in coastal defense. *Climate Change Economics*, **3(2)**, 1250008, doi:10.1142/S201000781250008X.

Loomis, J., P. Kent, L. Strange, K. Fausch, and A. Covich, 2000: Measuring the total economic value of restoring ecosystem services in an impaired river basin: results from a contingent valuation survey. *Ecological Economics*, **33**, 103-117.

Lucena, A.F.P., R. Schaeffer, and A.S. Szklo, 2010: Least cost-adaptation options for global climate change impacts on the Brazilian electric power system. *Global Environmental Change*, **20(2)**, 342-350.

Magat, W., K.W. Viscusi, and J. Huber, 1987: Risk-dollar tradeoffs, risk perceptions, and consumer behaviour. In: *Learning About Risk* [Viscusi, W. and W. Magat (eds.)]. Harvard University Press, Cambridge, MA, USA, pp. 83-97.

Margulis, S., C. Dubeux, and J. Marcovitch (coords.), 2011: *The Economics of Climate Change in Brazil: Costs and Opportunities*. Faculty of Economics, Business and Accounting of the University of São Paulo (FEAUSP), School of Economics, Business Administration and Accountancy, University of São Paulo, São Paulo, Brazil, 81 pp.

Markandya, A. and A. Chiabai, 2009: Valuing climate change impacts on human health: empirical evidence from the literature, *International Journal of Environmental Research and Public Health*, **6**, 759-786.

Markandya, A. and A. Mishra (eds.), 2011: *Costing Adaptation: Preparing for Climate Change in India*. The Energy and Resources Institute (TERI), TERI Press, New Delhi, India, 258 pp.

Markandya, A. and P. Nunes, 2012: Is the value of bioprospecting contracts too low? *International Journal of Ecological Economics and Statistics*, **26(3)**, 67-82.

Martinez-Alier, J., G. Munda, and J. O'Neill, 1998: Weak comparability of values as a foundation for ecological economics. *Ecological Economics*, **26**, 277-286.

Mathew, S., S. Truck, and A. Hendersen-Sellers, 2012: Kochi, India case study of climate change adaptation to floods: ranking government investment options. *Global Environmental Change*, **22**, 308-319.

Matrosov, E.S., S. Padula, and J.J. Harou, 2013: Selecting portfolios of water supply and demand management strategies under uncertainty – contrasting economic optimisation and 'robust decision making' approaches. *Water Resources Management*, **27**, 1123-1148.

Matthews, S., R. O'Connor, and A.J. Plantinga, 2002: Quantifying the impacts on biodiversity of policies for carbon sequestration in forests. *Ecological Economics*, **40(1)**, 71-87.

McCann, L. and K.W. Easter, 2000: Transaction costs of policies to reduce agricultural phosphorous in the Minnesota river. *Land Economics*, **75 (3)**, 402-414.

McGray, H., A. Hammill, R. Bradley, E.L. Schipper, and J.-E. Parry, 2007: *Weathering the Storm: Options for Framing Adaptation and Development*. World Resources Institute, Washington, DC, USA, 57 pp.

McKinley, D.C., M.G. Ryan, R.A. Birdsey, C.P. Giardina, M.E. Harmon, L.S. Heath, R.A. Houghton, R.B. Jackson, J.F. Morrison, B.C. Murray, D.E. Pataki, and K.E. Skog, 2011: A synthesis of current knowledge on forests and carbon storage in the United States. *Ecological Applications*, **21**, 1902-1924.

McMichael, A.J., D. Campbell-Lendrum, S. Kovats, S. Edwards, P. Wilkinson, T. Wilson, R. Nicholls, S. Hales, F. Tanser, D. LeSueur, M. Schlesinger, and N. Andronova, 2004: Global climate change. In: *Comparative Quantification of Health Risks:*

Global and Regional Burden of Disease due to Selected Major Risk Factors [Ezzati, M., A. Lopez, A. Rodgers, and C. Murray (eds.)]. World Health Organization (WHO), Geneva, Switzerland, pp. 1543-1649.

Mearns, R. and A. Norton (eds.), 2010: *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World*. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 319 pp.

Medellín-Azuara, J., J. Harou, M. Olivares, K. Madani, J. Lund, R. Howitt, S. Tanaka, M. Jenkins, and T. Zhu, 2008: Adaptability and adaptations of California's water supply system to dry climate warming. *Climatic Change*, **87(Suppl. 1)**, S75-S90.

Mendelsohn, R., 2000: Efficient adaptation to climate change. *Climatic Change*, **45**, 583-600.

Mendelsohn, R. and M. Balick, 1995: The value of undiscovered pharmaceuticals in tropical forests. *Economic Botany*, **49(2)**, 223-228.

Mendelsohn, R. and A. Dinar, 2003: Climate, water, and agriculture. *Land Economics*, **79(3)**, 328-341.

Mendelsohn, R. and J. Neumann (eds.), 1999: *The Impact of Climate Change on the US Economy*. Cambridge University Press, Cambridge, UK, 344 pp.

Mendelsohn, R., W.D. Nordhaus, and D. Shaw, 1994: The impact of global warming on agriculture: a Ricardian analysis. *The American Economic Review*, **84(4)**, 753-771.

Mendelsohn, R., A. Dinar, and L. Williams, 2006: The distributional impact of climate change on rich and poor countries. *Environment and Development Economics*, **11(02)**, 159-178, doi:10.1017/S1355770X05002755.

Mendelsohn, R., K. Emanuel, S. Chonabayashi, and L. Bakkensen, 2012: The impact of climate change on global tropical cyclone damage. *Nature Climate Change*, **2**, 205-209, doi:10.1038/NCLIMATE1357.

Mercer, J., I. Kelman, K., Lloyd, and S. Suchet-Pearson, 2008: Reflections on use of participatory research for disaster risk reduction. *Area*, **40(2)**, 172-183.

Michel-Kerjan, E., 2006: Disasters and public policy: can market lessons help address government failures. In: *2006 Ninety Ninth Annual Conference: NTA Proceedings from the 99th Annual Conference in Boston MA*. National Tax Association (NTA), Washington, DC, USA, pp. 179-187, www.ntanet.org/publications/nta-proceedings/122.html.

Millennium Ecosystem Assessment, 2005: *Ecosystems and Human Well-Being: Synthesis*. Island Press, Washington, DC, USA, 137 pp.

Miller, D., 2007: *National Responsibility and Global Justice*. Oxford University Press, Oxford, UK and New York, NY, USA, 298 pp.

Millner, A., S. Dietz, and G. Heal, 2010: *Ambiguity and Climate Policy*. NBER Working Paper No. 16050, National Bureau of Economic Research (NBER), Cambridge, MA, USA, 29 pp., www.nber.org/papers/w16050.pdf.

Ministry for Land Management, Tourism and Environment, 2007: *National Adaptation Plan of Action (NAPA)*. Ministry for Land Management, Tourism and Environment, Burundi, Republic of Burundi, Bujumbura, Burundi, 74 pp.

Moser, S.C. and J.A. Ekstrom, 2010: A framework to diagnose barriers to climate change adaptation. *Proceedings of the National Academy of Sciences of the United States of America*, **107(51)**, 22026-22031.

Mote, P.W., E.A. Parson, A.F. Hamlet, K.N. Ideker, W.S. Keeton, D.P. Lettenmaier, N.J. Mantua, E.L. Miles, D.W. Peterson, D.L. Peterson, R. Slaughter, and A.K. Snover, 2003: Preparing for climatic change: the water, salmon, and forests of the Pacific Northwest, *Climatic Change*, **61(1)**, 45-88.

Mu, J. and B.A. McCarl, 2011: *Adaptation to Climate Change: Land Use and Livestock Management in the U.S.* Selected paper presented at the 2011 Annual Meeting of the Southern Agricultural Economics Association, Corpus Christi, TX, February, 2011, 35 pp., ageconsearch.umn.edu/bitstream/98708/2/Climate_change_and_livestock_management_2011_%5B3%5Dx.pdf.

Mu, J., B.A. McCarl, and A.M. Wein, 2012: Adaptation to climate change: changes in farmland use and stocking rate in the U.S. *Mitigation and Adaptation Strategies for Global Change*, **18**, 713-730, doi:10.1007/s11027-012-9384-4.

Muñoz-Piña, C., A. Guevara, J.M. Torres, and J. Braña Varela, 2008: Paying for the hydrological services of Mexico's forests: analysis, negotiations and results. *Ecological Economics*, **65**, 725-736.

Muradian, R., E. Corbera, U. Pascual, N. Kosoy, and P. May, 2010: Reconciling theory and practice: an alternative conceptual framework for understanding payments for environmental services. *Ecological Economics*, **69**, 1202-1208.

Musgrave, R.A. and P.B. Musgrave, 1973: *Public Finance in Theory and Practice*. McGraw Hill, Inc., US, New York, NY, USA, 650 pp.

Naseem, A., D.J. Spielman, and S.W. Omamo, 2010: Private-sector investment in R&D: a review of policy options to promote its growth in developing-country agriculture. *Agribusiness*, **26**, 143-173.

Navrud, S. and R. Ready, 2007: *Environmental Value Transfer: Issues and Methods*. The Economics of Non-Market Goods and Resources Series, Book 9, Springer, Dordrecht, Netherlands, 290 pp.

National Research Council, 2005: *Valuing Ecosystem Services: Toward Better Environmental Decision-Making*. Committee on Assessing and Valuing the Services of Aquatic and Related Terrestrial Ecosystems, National Research Council, National Academies Press, Washington, DC, USA, 263 pp.

National Research Council, 2010: *Adapting to the Impacts of Climate Change*. America's Climate Choices: Panel on Adapting to the Impacts of Climate Change, Division on Earth and Life Studies, National Research Council, The National Academies Press, Washington, DC, USA, 272 pp.

New, M. and M. Hulme, 2000: Representing uncertainty in climate change scenarios: a Monte-Carlo approach. *Integrated Assessment*, **1(3)**, 203-213.

Nicholls, R. and R. Tol, 2006: Impacts and responses to sea level rise: a global analysis of the SRES scenarios over the twenty-first century. *Philosophical Transactions of the Royal Society A*, **364**, 1073-1095.

Nielsen, J.O. and A. Reenberg, 2010: Cultural barriers to climate change adaptation: a case study from Northern Burkina Faso. *Global Environmental Change*, **20**, 142-152.

Nordhaus, W., 2006: *The Economics of Hurricanes in the United States*. NBER Working Paper No.12813, National Bureau of Economic Research (NBER), Cambridge, MA, USA, 46 pp.

Nordhaus, W.D., 2008: *A Question of Balance: Weighing the Options on Global Warming Policies*. Yale University Press, New Haven, CT, USA and London, UK, 234 pp.

NRTEE, 2012: *Facing the Elements: Building Business Resilience in a Changing Climate*. Advisory Report, National Round Table on the Environment and the Economy (NRTEE), Ottawa, ON, Canada, 131 pp., collectionscanada.gc.ca/webarchives2/20130322175153/http://nrtee-trnee.ca/wp-content/uploads/2012/04/cp5-advisory-report.pdf.

O'Brien, K.L., R. Leichenko, U. Kelkar, H. Venema, G. Aandahl, H. Tompkins, A. Javed, S. Bhadwal, S. Barg, L. Nygaard, and J. West, 2004: Mapping vulnerability to multiple stressors: climate change and globalization in India. *Global Environmental Change*, **14**, 303-313.

O'Brien, K., B. Hayward, and F. Berkes, 2009: Rethinking social contracts: building resilience in a changing climate. *Ecology and Society*, **14(2)**, 12, www.ecologyandsociety.org/vol14/iss2/art12/.

O'Brien, K., A. St. Clair, and B. Kristoffersen, 2010: The framing of climate change: why it matters. In: *Climate Change, Ethics and Human Security* [O'Brien, K., A. St. Clair and B. Kristoffersen (eds.)]. Cambridge University Press, Cambridge, UK, pp. 3-22.

O'Brien, K., M. Pelling, A. Patwardhan, S. Hallegatte, A. Maskrey, T. Oki, U. Oswald-Spring, T. Wilbanks, and P.Z. Yanda, 2012: Toward a sustainable and resilient future. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 437-486.

O'Hara, J. and K. Georgakakos, 2008: Quantifying the urban water supply impacts of climate change. *Water Resources Management*, **22**, 1477-1497.

Olmstead, S.M., 2010: The economics of managing scarce water resources. *Review of Environmental Economics and Policy*, **4(2)**, 179-198.

Osberghaus, D., A. Dannenberg, T. Mennel, and B. Sturm, 2010a: The role of the government in adaptation to climate change. *Environment and Planning C: Government and Policy*, **28(5)**, 834-850.

Osberghaus, D., E. Finkerl, and M. Pohl, 2010b: *Individual Adaptation to Climate Change: The Role of Information and Perceived Risk*. ZEW Discussion Paper No. 10-061, Zentrum für Europäische Wirtschaftsforschung (ZEW) GmbH, Centre for European Economic Research, Mannheim, Germany, 31 pp., ftp://ftp.zew.de/pub/zew-docs/dp/dp10061.pdf.

Owour, B., W. Mauta, and S. Eriksen, 2011: Strengthening sustainable adaptation: examining interactions between pastoral and agropastoral groups in dryland Kenya. *Climate and Development*, **3(1)**, 42-58.

Oxfam, 2007: *Adapting to Climate Change: What's Needed in Poor Countries, and Who Should Pay*. Oxfam Briefing Paper No. 104, Oxfam International Secretariat, Oxford, UK, 47 pp.

Paavola, J. and W.N. Adger, 2006: Fair adaptation to climate change. *Ecological Economics*, **56**, 594-609.

Pagiola, S., 2008: Payments for environmental services in Costa Rica. *Ecological Economics*, **65(4)**, 712-724.

Pahl-Wostl, C., 2009: A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. *Global Environmental Change*, **19**, 354-365.

Pal, S., 2011: Impacts of CGIAR crop improvement and natural resource management research: a review of evidence. *Agricultural Economics Research Review*, **24**, 185-200.

Panayotou, T., J.D. Sachs, and A.P. Zwane, 2002: Compensation for 'meaningful participation' in climate change control: a modest proposal and empirical analysis. *Journal of Environmental Economics and Management*, **43(3)**, 437-454, doi:10.1006/jeem.2001.1189.

Parry, M., N. Arnell, P. Berry, D. Dodman, S. Fankhauser, C. Hope, S. Kovats, R. Nicholllas, D. Satterthwaite, R. Tiffin, and R. Wheeler, 2009: *Assessing the Costs of Adaptation to Climate Change: A Review of the UNFCCC and Other Recent Estimates*. International Institute for Environment and Development (IIED) and Grantham Institute for Climate Change, Imperial College London, London, UK, 111 pp.

Patt, A.G. and D. Schröter, 2008: Perceptions of climate risk in Mozambique: implications for the success of adaptation strategies. *Global Environmental Change*, **18**, 458-467.

Patt, A.G., D.P. van Vuuren, F. Berkhout, A. Aaheim, A.F. Hof, M. Isaac, and R. Mechler, 2009: Adaptation in integrated assessment modeling: where do we stand? *Climate Change*, **99**, 383-402, doi:10.1007/s10584-009-9687-y.

Patz, J.A., H.K. Gibbs, J.A. Foley, J.V. Rogers, and K.R. Smith, 2007: Climate change and global health: quantifying a growing ethical crisis. *EcoHealth*, **4(4)**, 397-405.

Pelling, M. and K. Dill, 2009: Disaster politics: tipping points for change in the adaptation of socio-political regimes. *Progress in Human Geography*, **34**, 21-37, doi:10.1177/0309132509105004.

Pelling, M., C. High, J. Dearing, and D. Smith, 2007: Shadow spaces for social learning: a relational understanding of adaptive capacity to climate change within organizations. *Environment and Planning A*, **40(4)**, 867-884.

Pendleton, L., P. King, C. Mohn, D.G. Webster, R.K. Vaughn, and P. Adams, 2008: *Estimating the Potential Economic Impacts of Climate Change on Southern California Beaches*. CEC-500-2009-033-D, Paper prepared by the California Climate Change Center as the result of work sponsored by the California Energy Commission (Energy Commission) and the California Environmental Protection Agency (Cal/EPA), 104 pp., www.energy.ca.gov/2009publications/CEC-500-2009-033/CEC-500-2009-033-D.PDF.

Persson, Å., R.J.T. Klein, C. Kehler Siebert, A. Atteridge, B. Müller, J. Hoffmaister, M. Lazarus, and T. Takama, 2009: *Adaptation Finance under a Copenhagen Agreed Outcome*. Research Report, Stockholm Environment Institute (SEI), Stockholm, Sweden, 187 pp. www.sei-international.org/mediamanager/documents/Publications/SEI-ResearchReport-PerssonA-AdaptationFinanceUnderACopenhagenAgreedOutcome-2009.pdf.

Peters, E. and P. Slovic, 1996: The role of affect and worldviews as orienting dispositions in the perception and acceptance of nuclear power. *Journal of Applied Social Psychology*, **26(16)**, 1427-1453.

Peterson, J.M. and Y. Ding, 2005: Economic adjustments to groundwater depletion in the high plains: do water-saving irrigation systems save water? *American Journal of Agricultural Economics*, **87(1)**, 147-159.

Pfeiffer, L. and C.Y. Lin, 2010: The effect of irrigation technology on groundwater use. *Choices*, 3rd Quarter, **25(3)**, www.choicesmagazine.org/magazine/pdf/article_147.pdf.

Pielke, R., Jr., 2007: Mistreatment of the economic impacts of extreme events in the Stern Review Report on the Economics of Climate Change. *Global Environmental Change*, **17(4)**, 302-310.

Plantinga, A.J. and J. Wu, 2003: Co-benefits from carbon sequestration in forests: evaluating reductions in agricultural externalities from and afforestation policy in Wisconsin. *Land Economics*, **79(1)**, 74-85.

Platt, R.H., 1999: *Disasters and Democracy: The Politics of Extreme Natural Events*. Island Press, Washington, DC, USA, 320 pp.

Podsakoff, P.M., S.B. MacKenzie, R.H. Moorman, and R. Fetter, 1990: Transformational leader behaviors and their effects on followers' trust in leader, satisfaction, and organizational citizenship behaviors. *Leadership Quarterly*, **1(2)**, 107-142.

Popp, D., 2004: *R&D Subsidies and Climate Policy: is there a "Free Lunch"?* NBER Working Paper No. 10880, National Bureau of Economic Research (NBER), Cambridge, MA, USA, 36 pp.

Porras, I., M. Grieg-Gran, and N. Neves, 2008: *All that Glitters: A Review of Payments for Watershed Services in Developing Countries*. IIED Natural Resource Issues 11, International Institute for Environment and Development (IIED), London, UK, 129 pp.

Portney, P.R. and J. Mullahy, 1986: Urban air quality and acute respiratory illness. *Journal of Urban Economics*, **20**, 21-38.

Purvis, M., P. Bares, and C. Hayes, 2008: A probabilistic methodology to estimate future coastal flood risk due to sea level rise. *Coastal Engineering*, **55(12)**, 1062-1073.

Qin, X.S., G.H. Huang, A. Chakma, X.H. Nie, and Q.G. Lin, 2008: A MCDM-based expert system for climate-change impact assessment and adaptation planning – a case study for the Georgia Basin, Canada. *Expert Systems with Applications*, **34(3)**, 2164-2179.

Ranger, N., A. Millner, S. Dietz, S. Fankhauser, A. Lopez, and G. Ruta, 2010: *Adaptation in the UK: A Decision-Making Process*. Policy Brief, Grantham Research Institute on Climate Change and the Environment and Center for Climate Change Economics and Policy, the London School of Economics and Political Science, London, UK, 61 pp., www.cccep.ac.uk/Publications/Policy/docs/PB-adaptation UK-ranger.pdf.

Ranger, N., S. Hallegatte, S. Bhattacharya, M. Bachu, S. Priya, K. Dhore, F. Rafique, P. Mathur, N. Naville, F. Henriet, C. Herweijer, S. Pohit, and J. Corfee-Morlot, 2011: A preliminary assessment of the potential impact of climate change on flood risk in Mumbai, *Climatic Change*, **104(1)**, 139-167.

Rao, K. and U. Hess, 2009: Scaling up in India: the public sector. In: *Index Insurance and Climate Risk: Prospects for Development and Disaster Management* [Hellmuth, M.E., D.E. Osgood, U. Hess, A. Moorhead, and H. Bhojwani (eds.)]. Climate and Society No. 2, International Research Institute for Climate and Society (IRI), New York, NY, USA, pp. 87-89.

Reeder, T., J. Wicks, L. Lovell, and O. Tarrant, 2009: Protecting London from tidal flooding: limits to engineering adaptation. In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, W.N., I. Lorenzoni, and K. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK, pp. 54-78.

Refsgaard, J.C., K. Arnbjerg-Nielsen, M. Drews, K. Halsnæs, E. Jeppesen, H. Madsen, A. Markandya, J.E. Olesen, J.R. Porter, and J.H. Christensen, 2013: The role of uncertainty in climate change adaptation strategies – a Danish water management example. *Mitigation and Adaptation Strategies for Global Change*, **18(3)**, 337-359.

Repetto, R., 2008: *The Climate Crisis and the Adaptation Myth*. Working Paper 13, Yale School of Forestry and Environmental Studies, New Haven, CT, USA, 20 pp.

Ribaudo, M.O., 1989: *Water Quality Benefits from the Conservation Reserve Program*. Agricultural Economic Report, Vol. 606, U.S. Department of Agriculture, Economic Research Service, Washington, DC, USA, 30 pp.

Rosenzweig, C., K.M. Strzepek, D.C. Major, A. Iglesias, D.N. Yates, A. McCluskey, and D. Hillel, 2004: Water resources for agriculture in a changing climate: international case studies. *Global Environmental Change*, **14**, 345-360.

Rosenzweig, C., W.D. Solecki, L. Parshall, B. Lynn, J. Cox, R. Goldberg, S. Hodges, S. Gaffin, R.B. Slosberg, P. Savio, F. Dunstan, and M. Watson, 2009: Mitigating New York City's heat island: integrating stakeholder perspectives and scientific evaluation. *Bulletin of the American Meteorological Society*, **90(9)**, 1297-1312.

Roy, J., 2000: The rebound effect: some empirical evidence from India. *Energy Policy*, **28(6-7)**, 433-438.

Saleth, R.M., A. Dinar, and J.A. Frisbie, 2012: Climate change, drought, and agriculture: the role of effective institutions and infrastructure. In: *Handbook on Climate Change and Agriculture* [Dinar, A. and R. Mendelsohn (eds.)]. Edward Elgar: Cheltenham, UK, pp. 466-485.

Samet, J.M., 2010: *Public Health: Adapting to Climate Change*. Issue Brief 10-06, Resources for the Future, Washington, DC, USA, 13 pp., www.rff.org/RFF/Documents/RFF-IB-10-06.pdf.

Samuelson, P.A., 1954: The pure theory of public expenditure. *Review of Economics and Statistics*, **36(4)**, 387-389.

Sartori, I. and A.G. Hestnes, 2007: Energy use in the life cycle of conventional and low-energy 30 buildings: a review article. *Energy & Buildings*, **39(3)**, 249-257.

Savage, L.J., 1951: The theory of statistical decisions. *Journal of the American Statistical Association*, **46(253)**, 55-67.

Schalatek, L., S. Nakhooda, S. Barnard, and A. Caravani, 2012: *Climate Finance Thematic Briefing: Adaptation Finance*. Overseas Development Institute (ODI), London, UK and Heinrich Böll Stiftung North America, Washington, DC, USA, 2 pp.

Schelling, T., 1992: Some economics of global warming. *American Economic Review*, **82(1)**, 1-14.

Schelling, T., 1997: The cost of combating global warming: facing the tradeoffs. *Foreign Affairs*, **76(6)**, 8-14.

Schlenker, W. and D.B Lobell, 2010: Robust negative impacts of climate change on African agriculture. *Environmental Research Letters*, **5(1)**, 014010, doi:10.1088/1748-9326/5/1/014010.

Schlenker, W. and M.J. Roberts, 2009: Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **106(37)**, 15594-15598.

Schlenker, W., M. Hanemann, and A. Fisher, 2005: Will US agriculture really benefit from global warming? Accounting for irrigation in the hedonic approach. *American Economic Review*, **95(1)**, 395-406.

Schlenker, W., W.M. Hanemann, and A.C. Fisher, 2006: The impact of global warming on U.S. agriculture: an econometric analysis of optimal growing conditions, *Review of Economics and Statistics*, **88(1)**, 113-125.

Schultz, K., 2012: Financing climate adaptation with a credit mechanism: initial considerations, *Climate Policy*, **12(2)**, 187-197.

Schwartz, P., 1996: *The Art of the Long View*. Double Day, New York, NY, USA, 272 pp.

Scott, D.J., C.J. Lemieux, and L. Malone, 2011: Climate services to support sustainable tourism and adaptation to climate change. *Climate Research*, **47(1)**, 111-122, doi:10.3354/cr00952.

SEGCC, 2007: *Confronting Climate Change: Avoiding the Unmanageable and Managing the Unavoidable* [Bierbaum, R.M., J.P. Holdren, M.C. MacCracken, R.H. Moss, and P.H. Raven (eds.)]. Report prepared for the 15th Session of the United Nations Commission on Sustainable Development by the United Nations-Sigma XI Scientific Expert Group on Climate Change (SEGCC), Sigma Xi, Research Triangle Park, NC, USA and United Nations Foundation, Washington, DC, USA, 144 pp., www.sigmaxi.org/programs/unseg/Full_Report.pdf.

Seo, S.N. and R. Mendelsohn, 2008a: An analysis of crop choice: adapting to climate change in South American farms. *Ecological Economics*, **67(1)**, 109-116.

Seo, S.N. and R. Mendelsohn, 2008b: Animal husbandry in Africa: climate change impacts and adaptations. *African Journal of Agricultural and Resource Economics*, **2(1)**, 65-82.

Seo, S.N. and R. Mendelsohn, 2008c: Measuring impacts and adaptations to climate change: a structural Ricardian model of African livestock management. *Agricultural Economics*, **38(2)**, 151-165.

Seo, S., R. Mendelsohn, A. Dinar, R. Hassan, and P. Kurukulasuriya, 2009a: A Ricardian analysis of the distribution of climate change impacts on agriculture across agro-ecological zones in Africa. *Environmental and Resource Economics*, **43(3)**, 313-332.

Seo, S.N., R. Mendelsohn, A. Dinar, and P. Kurukulasuriya, 2009b: Adapting to climate change mosaically: an analysis of African livestock management by agro-ecological zones. *The B.E. Journal of Economic Analysis & Policy*, **9(2)**, 1-35, doi:10.2202/1935-1682.1955.

Shogren, J. and L. Taylor, 2008: On behavioral environmental economics. *Review of Environmental Economics and Policy*, **2(1)**, 26-44.

Skees, J.R., B.J. Barnett, and A.G. Murphy, 2008: Creating insurance markets for natural disaster risk in lower income countries: the potential role for securitization. *Agricultural Finance Review*, **68**, 151-157.

Slovic, P., 1987: Perception of risk. *Science*, **236**, 280-285.

Smit, B. and J. Wandel, 2006: Adaptation, adaptive capacity and vulnerability. *Global Environmental Change*, **16(3)**, 282-292.

Smit, B., I. Burton, R. Klein, and J. Wandel, 2000: An anatomy of adaptation to climate change and variability. *Climatic Change*, **45**, 223-251.

Smith, J.B. and S.S. Lenhart, 1996: Climate change adaptation policy options. *Climate Research*, **6**, 193-201.

Sohngen, B., R. Mendelsohn, and R. Sedjo, 2001: A global model of climate change impacts on timber markets. *Journal of Agricultural and Resource Economics*, **26(2)**, 326-343.

Sperling, F., C. Valdivia, R. Quiroz, R. Valdivia, L. Angulo, A. Seimon, and I. Noble, 2008: *Transitioning to Climate Resilient Development: Perspectives from Communities in Peru*. World Bank Environment Department Papers, Paper No. 115, Climate Change Series, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 103 pp.

Spittlehouse, D.L. and R.B. Stewart, 2003: Adaptation to climate change in forest management. *BC Journal of Ecosystems and Management*, **4 (1)**, 1-11.

Squire, L. and H.G. van der Tack, 1975: *Economic Analysis of Projects*. The World Bank Publications, Johns Hopkins University Press, Baltimore, MD, USA, 104 pp.

Srinivasan, U.T., S.P. Carey, E. Hallstein, P.A.T. Higgins, A.C. Kerr, L.E. Koteen, A.B. Smith, R. Watson, J. Harte, and R.B. Norgaard, 2008: The debt of nations and the distribution of ecological impacts from human activities. *Proceedings of the National Academy of Sciences of the United States of America*, **105(5)**, 1768- 1773.

Stafford-Smith, M., L. Horrocks, A. Harvey, and C. Hamilton, 2011: Rethinking adaptation for a 4˚C world. *Philosophical Transactions of the Royal Society A*, **369**, 196-216.

Starret, D.A., 1988: *Foundations in Public Economics*. Cambridge University Press, New York, NY, USA, 315 pp.

Stavins, R.N., 1995: Transaction costs and tradeable permits. *Journal of Environmental Economics and Management*, **29(2)**, 133-148.

Stern, N., 2006: *Stern Review: Economics of Climate Change*. Cambridge University Press, Cambridge, UK, 692 pp.

Sterner, T., 2002: *Policy Instruments for Environmental and Natural Resource Management*. Resources for the Future, Washington, DC, USA, 503 pp.

Sterner, T. (ed.), 2011: *Fuel Taxes and the Poor: The Distributional Effects of Gasoline Taxation and Their Implications for Climate Policy*. RFF Press, Abingdon, UK and New York, NY, USA, 357 pp.

Sterner, T. and M. Persson, 2007: *An Even Sterner Review: Introducing Relative Prices into the Discounting Debate*. Resources for Future Discussion Paper RFF DP 07-37 July 2007, Washington, DC, USA, 21 pp.

Suarez, P. and A.G. Patt, 2004: Cognition, caution, and credibility: the risks of climate forecast application. *Risk Decision and Policy*, **9(1)**, 75-89.

Suarez, P., W. Anderson, V. Mahal, and T.R. Lakshmanan, 2005: Impacts of flooding and climate change on urban transportation: a system-wide performance assessment of the Boston Metro Area. *Transportation Research Part D: Transport and Environment*, **10(3)**, 231-244.

Surminski, S., 2010: *Adapting to the Extreme Weather Impacts of Climate Change – How Can the Insurance Industry Help?* ClimateWise Secretariat, London, UK, 43 pp.

Sutton, W., J. Srivastava, and J. Neumann, 2013: *Looking Beyond the Horizon: How Climate Change Impacts and Adaptation Responses Will Reshape Agriculture in Eastern Europe and Central Asia*. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 177 pp.

Swiss Re, 1998: *Floods – An Insurable Risk? A Market Survey*. Risk Perception Report, Swiss Reinsurance Company (Swiss Re), Zurich, Switzerland, 51 pp.

Tacconi, L., 2012: Redefining payments for environmental services. *Ecological Economics*, **73**, 29-36.

Tebaldi, C., R. Smith, D. Nychka, and L. Mearns, 2005: Quantifying uncertainty in projections of regional climate change: a Bayesian approach to the analysis of multi-model ensembles. *Journal of Climate*, **18**, 1524-1540.

TEEB, 2010: *The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature : A Synthesis of the Approach, Conclusions and Recommendations of TEEB*. The Economics of Ecosystems and Biodiversity (TEEB) hosted by the United Nations Environment Programme (UNEP), UNEP TEEB, Geneva, Switzerland, 36 pp.

Thaler, R., 1999: Mental accounting matters. *Journal of Behavioral Decision Making*, **12**, 183-206.

Tierney, K.J., 1995: *Impacts of Recent U.S. Disasters on Businesses: The 1993 Midwest Floods and the 1994 Northridge Earthquake*. Paper presented at the National Center for Earthquake Engineering Research Conference: "Economic Impacts of Catastrophic Earthquakes – Anticipating the Unexpected," New York, NY, September 12-13, 1995, Disaster Research Center, University of Delaware, Newark, DE, USA, 53 pp.

Tol, R.S.J., 1996: The damage costs of climate change towards a dynamic representation. *Ecological Economics*, **19(1)** 67-90.

Tol, R.S.J., 2005: Emission abatement versus development as strategies to reduce vulnerability to climate change: an application of FUND. *Environment and Development Economics*, **10(5)**, 615-629.

Tol, R.S.J. and G.W. Yohe, 2007: The weakest link hypothesis for adaptive capacity: an empirical test. *Global Environmental Change*, **17**, 218-227.

Tol, R.S.J., S. Fankhauser, and J.B. Smith, 1998: The scope for adaptation to climate change: what can we learn from the impact literature? *Global Environmental Change*, **8(2)**, 109-123.

Tol, R.S.J., T.E. Downing, O.J. Kuik, and J.B. Smith, 2004: Distributional aspects of climate change impacts. *Global Environmental Change*, **14**, 259-272.

Train, K., 1985: Discount rates in consumer's energy-related decisions: a review of the literature. *Energy*, **10(12)**, 1243-1253.

Transportation Research Board, 2008: *Potential Impacts of Climate Change on U.S. Transportation*. Transportation Research Board Special Report 290, Committee on Climate Change and U.S. Transportation, Division on Earth and Life Studies, National Research Council, the National Academies Press, Washington, DC, USA, 280 pp.

Trenberth, K.E., 2008: Observational needs for climate prediction and adaptation. *Bulletin of the World Meteorological Organization*, **57(1)**, 17-21.

Trope, Y. and N. Liberman, 2003: Temporal construal. *Psychological Review*, **110(3)**, 403-421.

Turpie, J.K., C. Marais, and J.N. Blignaut, 2008: The Working for Water Programme: evolution of a payments for ecosystem services mechanism that addresses both poverty and ecosystem service delivery in South Africa. *Ecological Economics*, **65**, 788-798.

Tversky, A. and D. Kahneman, 1974: Judgment under uncertainty: heuristics and biases. *Science*, New Series, **185(4157)**, 1124-1131.

Tversky, A. and E. Shafir, 1992: Choice under conflict: the dynamics of deferred decision. *Psychological Science*, **3(6)**, 358-361.

UNDP, 2007: *Human Development Report 2007/08: Fighting Climate Change: Human Solidarity in a Divided World.* United Nations Development Programme (UNDP), Palgrave McMillan, New York, NY, USA, 384 pp.

UNDP, 2009: *UNDP Methodology Guidebook for the Assessment of Investment and Financial Flows to Address Climate Change*. Version 1.0, United Nations Development Programme (UNDP), New York, NY, USA, 56 pp.

UNEP, 2006: *Marine and Coastal Ecosystems and Human Well-Being: A Synthesis Report Based on the Findings of the Millennium Ecosystem Assessment*. United Nations Environment Programme (UNEP), Nairobi, Kenya, 64 pp.

UNFCCC, 2002: *Annotated Guidelines for the Preparation of National Adaptation Programmes of Action*. Decision 28/CP.7, Least Developed Countries Expert Group, United Nations Framework Convention on Climate Change (UNFCCC), UNFCCC Secretariat, Bonn, Germany, 41 pp., unfccc.int/files/cooperation_and_support/ldc/application/pdf/annguide.pdf.

UNFCCC, 2007: *Investment and Financial Flows to Address Climate Change*. Background paper on the analysis of existing and planned investment and financial flows relevant to the development of effective and appropriate international response to climate change, United Nations Framework Convention on Climate Change (UNFCCC), UNFCCC Secretariat, Bonn, Germany, 272 pp.

UNFCCC, 2008: *Investment and Financial Flows to Address Climate Change: An Update*. Technical Paper, Bonn Document No. FCCC/TP/2008/7, 26 November 2008, United Nations Framework Convention on Climate Change (UNFCCC), UNFCCC Secretariat, Bonn, Germany, 111 pp.

Verheyen, R., 2002: Adaptation to the impacts of anthropogenic climate change – the international legal framework. *Review of European Community & International Environmental Law*, **11(2)**, 129-143.

Verheyen, R., 2005: *Climate Change Damage and International Law: Prevention Duties and State Responsibility*. Developments in International Law, Vol. 54, Martinus Nijhoff, Leiden, Germany and Boston, MA, USA, 406 pp.

Verlade, S., Y. Malhi, D. Moran, J. Wright, and S. Hussain, 2005: Valuing the impacts of climate change on protected areas in Africa. *Ecological Economics*, **53(1)**, 21-33.

Viguie, V. and S. Hallegatte, 2012: Trade-offs and synergies in urban climate policies. *Nature Climate Change*, **2**, 334-337, doi:10.1038/NCLIMATE1434.

Viscusi, W.K. and J.E. Aldy, 2003: The value of a statistical life: a critical review of market estimates throughout the world. *Journal of Risk and Uncertainty*, **5**, 5-76.

Vivid Economics, 2010: *Promoting Economic Growth when the Climate is Changing*. Report prepared for UK Department of International Development (DIFID) by Vivid Economics, Vivid Economics, London, UK, 42 pp.

Vorosmarty, C.J., P. Green, J. Salisbury, and R.B. Lammers, 2000: Global water resources: vulnerability from climate change and population growth. *Science*, **289**, 284-288.

Wang, W.W. and B.A. McCarl, 2013: Temporal investment in climate change adaptation and mitigation. *Climate Change Economics*, **04(02)**, 1350009, doi:10.1142/S2010007813500097.

Ward, P.J., K.M. Strzepek, W.P. Pauw, L.M. Brander, G.A. Hughes, and J.C.J.H. Aerts, 2010: Partial costs of global climate change adaptation for the supply of raw industrial and municipal water: a methodology and application. *Environmental Research Letters*, **5(4)**, 044011, doi:10.1088/1748-9326/5/4/044011.

Watkiss, P. (ed.), 2011: *The Climate Cost Project. Final Report, Volume 1: Europe.* Published by the Stockholm Environment Institute (SEI), Stockholm, Sweden, ISBN 978-91-86125-35-6, www.climatecost.cc/reportsandpublications.html.

Watkiss, P. and A. Hunt, 2010: *Review of Adaptation Costs and Benefits Estimates in Europe for SOER 2010*. Contribution to the EEA SOER 2010, Report prepared for the European Environment Agency (EEA) under the Framework contract for economic support (EEA/IEA/09/002) – Lot 2 'Climate change adaptation: costs and benefits', Metroeconomica Economic and Environmental Consultants and Paul Watkiss Associates, Bath, UK, 74 pp.

Weitzman, M.L., 2009: On modeling and interpreting the economics of catastrophic climate change. *The Review of Economics and Statistics*, **91**, 1-19.

West, C.T. and D.G. Lenze, 1994: Modeling the regional impact of natural disasters and recovery: a general framework and an application to Hurricane Andrew. *International Regional Science Review*, **17(2)**, 121-150.

West, J.J., M.J. Small, and H. Dowlatabadi, 2001: Storms, investor decisions, and the economic impacts of sea level rise. *Climatic Change*, **48**, 317-342.

White, H. and E. Masset, 2008: *An Impact Evaluation of India's Second And Third Andhra Pradesh Irrigation: A Case of Poverty Reduction with Low Economic Returns*. The World Bank Independent Evaluation Group (IEG), The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 130 pp.

Wilbanks, T., 2007: Scale and sustainability. *Climate Policy*, **7(4)**, 278-287.

Wilbanks, T., 2010: Research and development priorities for climate change mitigation and adaptation. In: *Dealing with Climate Change: Setting a Global Agenda for Mitigation and Adaptation* [Pachauri, R. (ed.)]. The Energy Resources Institute (TERI), TERI Press, New Delhi, India, pp. 77-99.

Wilbanks, T. and J. Sathaye, 2007: Integrating mitigation and adaptation as responses to climate change: a synthesis. *Mitigation and Adaptation Strategies for Global Change*, **12(5)**, 957-962.

Wilby, R.L. and S. Dessai, 2010: Robust adaptation to climate change. *Weather*, **65**, 180-185.

Williamson, O.E., 1979: Transaction-cost economics: the governance of contractual relations. *Journal of Law and Economics*, **22(2)**, 233-261.

Willows, R. and R. Connell (eds.), 2003: *Climate Adaptation: Risk, Uncertainty and Decision-Making*. UKCIP Technical Report, UK Climate Impacts Programme (UKCIP), UKCIP, Oxford, UK, 154 pp., www.ukcip.org.uk/wordpress/wp-content/PDFs/UKCIP-Risk-framework.pdf.

Wing, I.S. and K. Fisher-Vanden, 2013: Confronting the challenge of integrated assessment of climate adaptation: a conceptual framework. *Climatic Change*, **117(3)**, 497-514.

World Bank, 2006: *Clean Energy and Development: Towards an Investment Framework*. DC2006-0002, prepared for the April 5, 2006 meeting of the Development Committee, Environmentally and Socially Sustainable Development Vice Presidency, Infrastructure Vice Presidency, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 146 pp.

World Bank, 2007: *Results of Preparation Work on the Design of a Caribbean Catastrophe Risk Insurance Facility*. Background document, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 68 pp.

World Bank, 2009: *World Development Report 2010: Development and Climate Change*. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 417 pp.

World Bank, 2010a: *Economics of Adaptation to Climate Change: Synthesis Report*. The World Bank Group, Washington, DC, USA, 136 pp., climatechange.worldbank.org/sites/default/files/documents/EACCSynthesisReport.pdf.

World Bank, 2010b: *Economics of Adaptation to Climate Change: Bangladesh, Vol. 1, Main Report.* The World Bank Group, Washington, DC, USA, 102 pp., climatechange.worldbank.org/sites/default/files/documents/EACC_Bangladesh.pdf.

World Bank, 2010c: *Economics of Adaptation to Climate Change: Samoa*. The World Bank Group, Washington, DC, USA, 58 pp., climatechange.worldbank.org/sites/default/files/documents/EACC_Samoa.pdf.

World Bank, 2010d: *Economics of Adaptation to Climate Change: Vietnam*. The World Bank Group, Washington, DC, USA, 84 pp., climatechange.worldbank.org/sites/default/files/documents/EACC_Vietnam.pdf.

World Bank, 2012: *Inclusive Green Growth: The Pathway to Sustainable Development*. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 171 pp.

World Bank, 2013: *World Development Report 2014: Risk and Opportunities – Managing Risk for Development*. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 343 pp.

World Bank and United Nations, 2010: *Natural Hazards UnNatural Disasters: The Economics of Effective Prevention*. The World Bank and the United Nations, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 254 pp.

WUCA, 2010: *Decision Support Planning Methods: Incorporating Climate Change Uncertainties into Water Planning*. Water Utility Climate Alliance (WUCA), San Francisco, CA, USA, 102 pp.

Wunder, S., 2005: *Payments for Environmental Services: Some Nuts and Bolts*. CIFOR Occasional Paper No. 42, Center for International Forestry Research (CIFOR), Bogor, Indonesia, 24 pp.

Wunder, S. and M. Albán, 2008: Decentralized payments for environmental services: the cases of Pimampiro and PROFAFOR in Ecuador. *Ecological Economics*, **65(4)**, 685-698.

Wunder, S. and J. Börner, 2011: Ch. 11: Changing land uses in forestry and agriculture through payments for environmental service. In: *Climate Change and Land Policies* [Ingram, G.K. and Y.-H. Hong (eds.)]. Lincoln Institute of Land Policy, Cambridge, MA, USA, pp. 277-304, www.lincolninst.edu/pubs/dl/2042_1364_LP2010-ch11-Changing-Land-Uses-in-Forestry-and-Agriculture-Through-Payments-for-Environmental-Services.pdf.

Wunder, S., S. Engel, and S. Pagiola, 2008: Taking stock: A comparative analysis of payments for environmental services programs in developed and developing countries. *Ecological Economics*, **65(4)**, 834-852.

Wünscher, T., S. Engel, and S. Wunder, 2008: Spatial targeting of payments for environmental services: a tool for boosting conservation benefits. *Ecological Economics*, **65**, 822-833.

Yohe, G. and R. Leichenko, 2010: Adopting a risk-based approach. *Annals of the New York Academy of Sciences*, **1196**, 29-40.

Yohe, G., J. Neumann, and H. Ameden, 1995: Assessing the economic cost of greenhouse induced sea level rise: methods and applications in support of a national survey. *Journal of Environmental Economics and Management*, **29(Suppl.)**, S78-S97.

Yohe, G., J. Neumann, P. Marshall, and H. Ameden, 1996: The economic cost of greenhouse induced sea level rise in the United States. *Climatic Change*, **32**, 387-410.

Yohe, G., K. Knee, and P. Kirshen, 2011: On the economics of coastal adaptation solutions in an uncertain world. *Climatic Change*, **106(1)**, 71-92.

Zhang, Y.W., A.D. Hagerman, and B.A. McCarl, 2013: How climate factors influence the spatial distribution of Texas cattle breeds, *Climatic Change*, **118(2)**, 183-195.

18 Detection and Attribution of Observed Impacts

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This chapter should be cited as:
Cramer, W., G.W. Yohe, M. Auffhammer, C. Huggel, U. Molau, M.A.F. da Silva Dias, A. Solow, D.A. Stone, and L. Tibig, 2014: Detection and attribution of observed impacts. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 979-1037.

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Executive Summary

Evidence has grown since the Fourth Assessment Report (AR4) that impacts of recent changes in climate on natural and human systems occur on all continents and across the oceans. This conclusion is strengthened both by new and longer term observations and through more extensive analyses of existing data. {18.3-6}

Reported impacts are caused by changes in climate that deviate from historical conditions, irrespective of the driver of climate change. Most reported impacts of climate change are attributed to warming and/or shifts in precipitation patterns. There is also emerging evidence of impacts of ocean acidification. Only some robust attribution studies and meta-analyses link responses in physical and biological systems to *anthropogenic* climate change. {18.1, 18.3-5}

For many natural systems there is new or stronger evidence for substantial and wide-ranging impacts of climate change. These systems include the cryosphere, water resources, coastal systems, and ecosystems on land and in the ocean. {18.3}

Impacts of climate change on the hydrological cycle, and notably the availability of freshwater resources, have been observed on all continents and many islands. Glaciers continue to shrink worldwide, as a result of climate change (*high confidence*), affecting runoff and water resources downstream. Climate change is the main driver of permafrost warming and thawing in both high-latitude and high-elevation mountain regions (*high confidence*). Hydrological systems have changed in many regions because of changing precipitation or melting cryosphere, affecting water resources, water quality, and sediment transport (*medium confidence*). {18.3.1, 18.5, Figure 18-2}

Across all climate zones and continents, the major role of climate change and increasing atmospheric carbon dioxide (CO_2) on terrestrial and freshwater ecosystems has been confirmed by new and stronger evidence on phenology (*high confidence*), productivity (*low confidence*), distribution ranges (*medium confidence*), and other processes, affecting an increasing number of species and ecosystems. The majority of species extinctions and the recession of the Amazon forest cannot be attributed reliably to climate change. Major climate-driven changes occur in the Arctic region (*high confidence*), the boreal forest (*low confidence*), and many freshwater ecosystems (*low* to *high confidence*, region-dependent). {18.3.2, 18.5}

Despite the known sensitivity of coastal systems to sea level rise, local natural and human perturbations preclude a confident detection of sea level-related impacts of climate change. Climate change has had a major role in observed changes in abundance and distribution of many coastal species (*medium confidence*). {18.3.3}

The physical and chemical properties of oceans (including the extent of Arctic sea ice) have changed significantly over the past 6 decades, due to anthropogenic climate change. Marine organisms have moved to higher latitudes and changed their depth distribution or their phenology, mostly as a result of the warming (*high confidence*). Coral reefs have experienced increased mass bleaching and mortality, driven mainly by warming (*high confidence*). {18.3.3-4, 18.5, Table 18-8, Box 18-2}

Substantial new evidence has been collected on sensitivities of human systems to climate change. Climate change-related impacts on human systems are often dominated by effects of changing social and economic factors. {18.4}

Production of wheat and maize globally and in many regional systems has been impacted by climate change over the past several decades (*medium confidence*). The impacts of climate change on rice and soybean have been small in major production regions and globally (*medium confidence*). Crop production has increased in some mid-latitude regions (United Kingdom, Northeast China) (*high confidence*). Evidence of observed climate change impacts on food systems other than agricultural crops and fisheries is limited. {18.4.1}

Economic losses due to extreme weather events have increased globally, mostly due to increase in wealth and exposure, with a possible influence of climate change (*low confidence*). {18.4.3}

There has been a shift from cold- to heat-related mortality in some regions as a result of warming (*medium confidence*), but despite many well-documented sensitivities of human health to other aspects of weather, clear evidence of an additional observed climate change impact on health outcomes is lacking. {18.4.4}

Livelihoods of indigenous peoples in the Arctic have been altered by climate change, through impacts on food security and traditional and cultural values (*medium confidence*). There is emerging evidence of climate change impacts on livelihoods of indigenous people in other regions. {18.4.6, Box 18-5, Table 18-9}

There is emerging literature on the impact of climate change on poverty, working conditions, violent conflict, migration, and economic growth from various parts of the world, but evidence for detection or attribution to climate change remains *limited*. {18.4}

Regional impacts of climate change have now been observed at more locations than before, on all continents and across ocean regions. In many regions, impacts of climate change are now detected also in the presence of strong confounding factors such as pollution or land use change. {18.6.2}

"Cascading" impacts of climate change from physical climate through ecosystems on people can now be detected along chains of evidence. Examples include systems in the cryosphere, the oceans, and forests. In these cases, confidence in attribution to observed climate change decreases for effects further down the impact chain. {18.6.3}

Evaluation of observed impacts of climate change supports risk assessment of climate change for four of the "Reasons for Concern" developed by earlier IPCC assessments. (1) Impacts related to *Risks to Unique and Threatened Systems* are now manifested for several systems (Arctic, glaciers on all continents, warm-water coral systems). (2) High-temperature spells have impacted one system with *high confidence* (coral reefs), indicating *Risks Associated with Extreme Weather Events*. Elsewhere, extreme events have caused increasing impacts and economic losses, but there is only *low confidence* in attribution to climate change for these. (3) Though impacts of climate change have now been documented globally with unprecedented coverage, observations are still insufficient to address the spatial or social disparities underlying the *Risks Associated with the Distribution of Impacts*. (4) *Risks Associated with Aggregated Impacts*: large-scale impacts, indicated by unified metrics, have been found for the cryosphere (ice volume, *high confidence*), terrestrial ecosystems (net productivity, carbon stocks, *medium-high confidence*), and human systems (crop yields, disaster losses, *low-medium confidence*). (5) R*isks Associated with Large-Scale Singular Events*: impacts that demonstrate irreversible shifts with significant feedback potential in the Earth system have yet to be observed, but there is now *robust evidence* of early warning signals in observed impacts of climate change that indicate climate-driven large-scale regime shifts for the Arctic region and the tropical coral reef systems. {18.6.4}

Though evidence is improving, there is a persistent gap in the knowledge regarding how certain parts of the world are being affected by observed climate change. Data collection and monitoring are in need to gain wider coverage. Research to improve the conceptual basis, timeliness, and knowledge about detection and attribution is needed in particular for human systems. {18.2, 18.7}

18.1. Introduction

This chapter synthesizes the scientific literature on the detection and attribution of observed changes in natural and human systems in response to observed recent climate change. For policy makers and the public, detection and attribution of observed impacts will be a key element to determine the necessity and degree of mitigation and adaptation efforts. For most natural and essentially all human systems, climate is only one of many drivers that cause change—other factors such as technological innovation, social and demographic changes, and environmental degradation frequently play an important role as well. Careful accounting of the importance of these and other confounding factors is therefore an important part of the analysis.

At any given location, observed recent climate change has happened as a result of a combination of natural, longer term fluctuations and anthropogenic alteration of forcings. To inform about the sensitivity of natural and human systems to ongoing climate change, the chapter assesses the degree to which detected changes in such systems can be attributed to all aspects of recent climate change. For the development of adaptation policies, it is less important whether the observed changes have been caused by anthropogenic climate change or by natural climate fluctuations. Where possible, the relative importance of anthropogenic drivers of climate change is assessed as well.

18.1.1. Scope and Goals of the Chapter

Previous assessments, notably in the IPCC Fourth Assessment Report (AR4; Rosenzweig et al., 2007), indicated that numerous physical and biological systems are affected by recent climate change. Owing to a limited number of published studies, human systems received comparatively little attention in these assessments, with the exception of the food system, which is a coupled human-natural system. This knowledge base is growing rapidly, for all types of impacted systems, but the disequilibrium remains (see also Section 1.1.1, Figure 1-1). The great majority of published studies attribute local to regional changes in affected systems to local to regional climate change.

The objective of the assessment was to cover the growing knowledge about detection and attribution of impacts as exhaustively as possible. To improve coverage across sectors and regions, the work was linked directly to the assessments made by most other chapters of the report. This ensured that knowledge gained in the expert assessments of any given sector, system, or region found its way into this chapter. This chapter uses a consistent set of definitions for detection and attribution (elaborated in Section 18.2.1—these differ from those found in some other chapters).

This chapter first reviews methodologies and definitions for detection and attribution, including the uncertainties that are inherent in such assessments (Section 18.2). It then assesses the scientific knowledge base that has developed since the AR4, focusing on the different types of impacted systems. The assessment covers the state of knowledge across major natural (Section 18.3) and human systems (Section 18.4), based largely on the respective sectoral chapters of this report (Chapters 3 to 7, 10 to 13). Assessment in confidence of the existence and cause of impacts is made according to the definitions elaborated in Section 18.2.1.2. Based on this material, and on regional assessments mostly drawn from the regional chapters of this report (Chapters 22 to 30), an assessment is made to highlight regional impacts and also to identify the regional pattern of observed impacts around the globe (Section 18.5). A synthesis (Section 18.6) and an analysis of research and knowledge gaps (Section 18.7) conclude the chapter.

18.1.2. Summary of Findings from the Fourth Assessment Report

Based on Rosenzweig et al. (2007), IPCC (2007a, p. 8) reported that "observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases." In particular, they highlighted several areas where this general conclusion was supported by specific conclusions that were reported with *high confidence*:

- Changes in snow, ice, and frozen ground had increased ground instability in mountains and other permafrost regions; these changes had led to changes in some Arctic and Antarctic ecosystems and produced increases in the number and size of glacial lakes.
- Some hydrological systems had been affected by increased runoff and earlier spring peak discharges; in particular many glacier- and snow-fed rivers and lakes had warmed, producing changes in their thermal structures and water quality.
- Spring events had appeared earlier in the year so that some terrestrial ecosystems had moved poleward and upward; these shifts in plant and animal ranges were attributed to recent warming.
- Shifts in ranges and changes in algal, plankton, and fish abundance as well as changes in ice cover, salinity, oxygen levels, and circulation had been associated with rising water temperatures in some marine and freshwater systems.

In terms of a global synthesis, this assessment noted "that it is *likely* that anthropogenic warming over the last three decades has had a discernible influence on many physical and biological systems" (IPCC, 2007a, p. 9). Though it was based on analyses of a very large number of observational data sets, the assessment noted a lack of geographic balance in data and literature on observed changes, with marked scarcity in low- and middle-income countries.

Evidence reported for human systems was scarce. IPCC (2007a, p. 9) concluded with *medium confidence* only that, "other effects of regional climate change on […] human environments are emerging, although many are difficult to discern due to adaptation and non-climatic drivers." They especially noted effects of temperature increases on agricultural and forestry management practices in the higher latitudes of the Northern Hemisphere (NH), various aspects of human health, and some human activities in snow- and glacier-dominated environments.

18.2. Methodological Concepts for Detection and Attribution of Impacts of Climate Change

There are substantial challenges to the detection and assessment of the impacts of climate change on natural and human systems. Virtually all

such systems are affected by factors other than climate change. Isolating the impacts of climate change therefore requires controlling for the effects of other factors. The problem is further complicated by the ability of many systems to adapt to climate change. In this section we summarize the concepts underlying the detection and attribution of impacts of climate change and the requirements for addressing the main challenges.

18.2.1. Concepts and Approaches

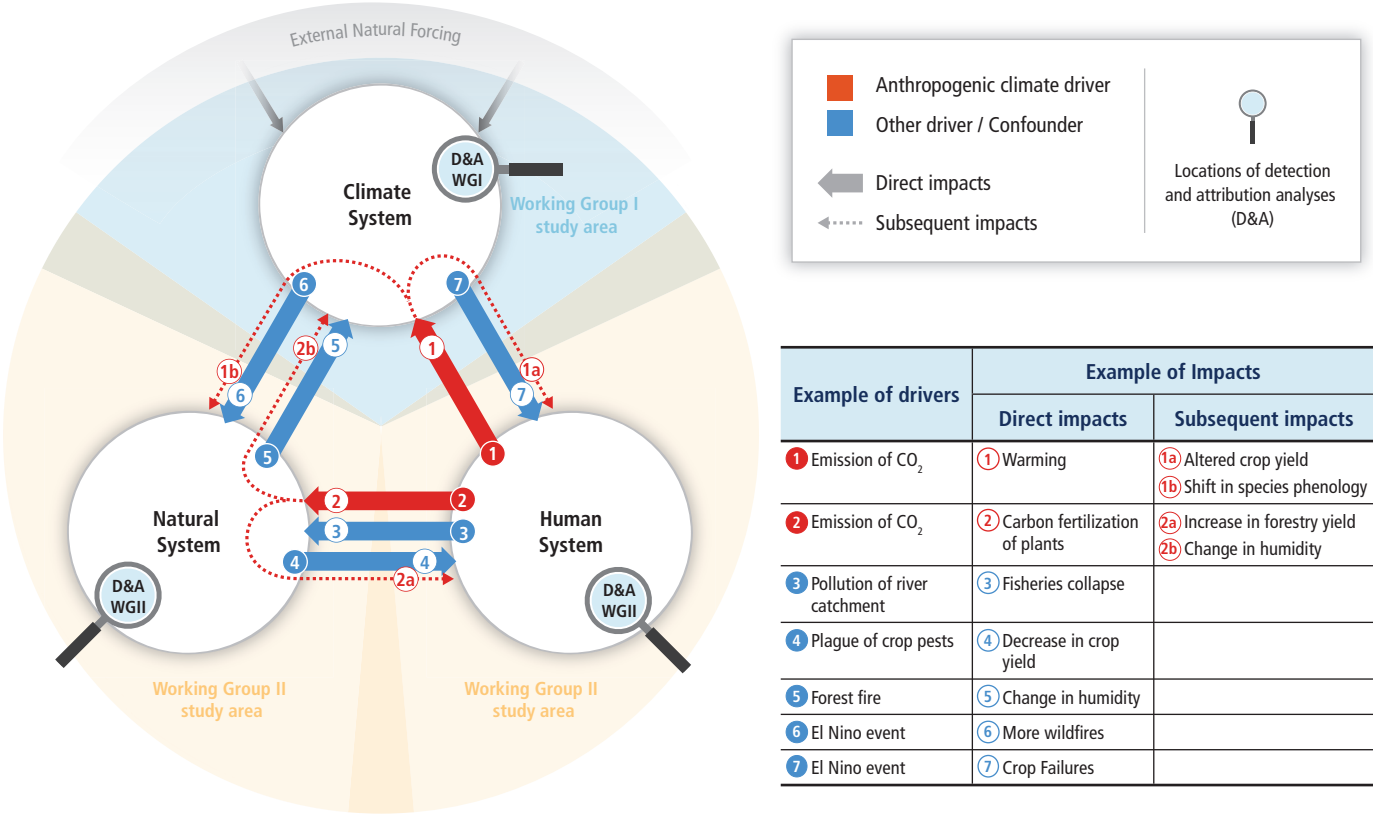
18.2.1.1. Detecting and Attributing Change in the Earth System

Detection and attribution is concerned with assessing the causal relationship between one or more drivers and a responding system. From an analysis perspective, the Earth system can be separated into three coupled subsystems, referred to here as the climate system, the natural system, and the human system (Figure 18-1). Separation of drivers from a responding system is a crucial element of formal detection and attribution analysis. Many external drivers may influence any system, including the changing climate and other confounding factors (Hegerl et al., 2010). Each of the three subsystems affects the other two directly or indirectly. For example, the human system may directly affect the natural system through deforestation, which in turn affects the climate system through changes in albedo; this can alter surface temperatures, which in turn feed back on natural and human systems. If an observed change in the human system impacts the climate system, we call this an anthropogenic driver of climate change.

In this chapter we assess the impacts of *climate change*, where climate change refers to any long-term trend in climate, irrespective of its cause (see Glossary). The great majority of published scientific studies support this type of assessment only. Some studies directly address the detection of and attribution to *anthropogenic climate change*, relating observed impacts, via the climate, to anthropogenic emissions of greenhouse gases and other human activities. Because of the complexity of the causal chain, investigation of this relationship is exceptionally challenging (Parmesan et al., 2011). The findings from such studies are explicitly highlighted in the chapter.

18.2.1.2. Concepts of Detection and Attribution of Climate Change Impacts Used in this Chapter

"Detection of impacts" of climate change addresses the question of whether a natural or human system is changing beyond a specified baseline that characterizes its behavior in the absence of climate change (Stone et al., 2013). The baseline may be stationary or non-stationary (e.g., due to land use change), and needs to be clearly defined. This definition of the detection of climate change impacts differs from that in WGI AR5 Chapter 10 which concerns any change in a climate variable, regardless of its cause. The definition adopted here focuses explicitly



Example of drivers	Example of Impacts	
	Direct impacts	Subsequent impacts
1 Emission of CO_2	1 Warming	1a Altered crop yield 1b Shift in species phenology
2 Emission of CO_2	2 Carbon fertilization of plants	2a Increase in forestry yield 2b Change in humidity
3 Pollution of river catchment	3 Fisheries collapse	
4 Plague of crop pests	4 Decrease in crop yield	
5 Forest fire	5 Change in humidity	
6 El Nino event	6 More wildfires	
7 El Nino event	7 Crop Failures	

Figure 18-1 | Schematic of the subject covered in this chapter. The Earth system consists of three coupled and overlapping systems. Direct drivers of the human system on the climate system are denoted with a red arrow; some of these drivers may also directly affect natural systems. These effects can in turn influence other systems (dashed red arrows). Further influences of each of the systems on each other (confounding factors) that do not involve climate drivers are represented by blue arrows. Examples of drivers and their impacts are given in the table. Adapted from Stone et al. (2013).

Box 18-1 | Quantitative Synthesis Assessment of Detection and Attribution Studies in Ecological Systems

The wealth of observations in ecological systems now permits the application of quantitative tools for synthesis assessment of detection and attribution (Root et al., 2005). These tools include associative pattern analyses (e.g., Rosenzweig et al., 2008) and regression analyses (Chen, I.C. et al., 2011), which compare expected changes due to anthropogenic climate change across multiple studies against observed changes.

Quantitative synthesis assessments have been particularly prominent in ecology, where measures of phenology (timing of seasonal events) and geographical range can be assembled across species into standardized indices (Parmesan and Yohe, 2003; Rosenzweig et al., 2008; Chen, I.C. et al., 2011; Poloczanska et al., 2013; Rosenzweig and Neofotis, 2013). Confidence in the detection of general patterns of change in these indices can increase with the number of species/ecosystems observed, the number of independent studies, the geographical distribution of these observations, the temporal depth and resolution of the data, and the representativeness of species/ecosystems and locations studied. However, increasing spatial coverage, numbers of species, and so forth does not *a priori* increase confidence that climate change is a more credible explanation for biological change than alternative hypotheses. Additional data can contribute to increased confidence in causal relationships, that is, attribution, in a synthesis assessment when it provides new evidence for explicit testing against a credible range of alternative hypotheses.

on the impact of climate change and not on trends related to other factors. The statement of detection is binary: an impact has or has not been detected.

"Attribution" addresses the question of the magnitude of the contribution of climate change to a change in a system. In practice, an attribution statement indicates how much of the observed change is due to climate change with an associated confidence statement. Hence, attribution requires the evaluation of the contributions of all external drivers to the system change. In this chapter we simplify the assessment of this relative contribution by specifying whether observed climate change has had a "minor role" or a "major role" in the overall change in the impacted system. A major role is assessed if the past behavior of the system would have been grossly different in the absence of the observed climate change.

18.2.2. Challenges to Detection and Attribution

Two broad challenges to the detection and attribution of climate change impacts relate to observations and process understanding. On the observational side, high-quality, long-term data relating to natural and human systems and the multiple factors affecting them are rare. In addition, the detection and attribution of climate change impacts requires an understanding of the processes by which climate change, in conjunction with other factors, may affect the system in question (see also Box 18-1). These processes can be nonlinear—for example, involving threshold effects (e.g., De Young and Jarre, 2009; Wassmann and Lenton, 2012)—and non-local in both space and time, involving lagged responses and trans-regional effects due, for example, to trade or migration.

Conclusions about the effect of climate change on natural and human systems in this report are based on a synthesis of findings in the scientific literature. A potential problem arises through the preferential publication of papers reporting statistically significant findings (Parmesan and Yohe, 2003). Methods exist for detecting and correcting for publication bias in formal quantitative synthesis analysis (Rothstein et al., 2005; Menzel et al., 2006), but these methods cannot be applied in all situations (Kovats et al., 2001). While the assessment in this chapter considers findings in the context of consistency across studies, regions, and similar systems, it has not been possible to quantitatively account for selection bias and to fully differentiate it from the lack of monitoring for some regions and systems.

18.3. Detection and Attribution of Observed Climate Change Impacts in Natural Systems

The following section provides a synthesis of findings with regard to freshwater resources, terrestrial and inland water systems, coastal systems, and oceans, which are documented in greater detail in Chapters 3, 4, 5, 6, and 30, respectively. It also incorporates evidence from regional chapters and further available literature.

18.3.1. Freshwater Resources

Impacts of climate change on the hydrological cycle, and notably the availability of freshwater resources, have been observed on all continents and many islands, with different characteristics of change in different regions (Chapters 3, 22 to 29; WGI AR5 Chapters 2 and 10). Figure 18-2 presents a synthesis of confidence in detection of global scale changes in freshwater resources and related systems (notably slope stability and erosion), and their attribution to climate change. Frozen components of freshwater systems tend to show higher confidence in detection and attribution, while components that are strongly influenced by non-climatic drivers, such as river flow, have lower confidence.

18.3.1.1. The Cryosphere

Most components of the cryosphere (glaciers, ice sheets, and floating ice shelves; sea, lake, and river ice; permafrost and snow) have undergone significant changes during recent decades (*high confidence*), related to climatic forcing (*high confidence*; WGI AR5 Chapter 4). It is *likely* that there is an anthropogenic component in the changes observed in Arctic sea ice, Greenland's surface melt, glaciers, and snow cover (WGI AR5 Section 10.5). Glaciers continue to shrink worldwide, with regional variations. It is *likely* that a substantial part of the glacier mass loss is due to anthropogenic warming (WGI AR5 Section 10.5.2.2). Climate change has a major role in the absolute contribution of ice loss from glaciers and ice caps to sea level rise, which has increased since the early 20th century and has now been close to 1 mm yr^{-1} for the past 2 decades (WGI AR5 Sections 4.3.3, 4.4.3), around a third of total observed sea level rise. Recent mass loss of ice sheets and glaciers has accelerated isostatic land uplift in the North Atlantic Region (Jiang et al., 2010). In several high-mountain regions, slope instabilities have occurred as a consequence of recent glacier downwasting (*high confidence*; Vilímek et al., 2005; Haeberli and Hohmann, 2008; Huggel et al., 2011).

The role of climate in changes in runoff decreases from major to minor as the distance from glaciers increases and other non-climatic factors become more important. Runoff from glacier areas has increased for catchments in western and southwestern China over the past several decades, and in western Canada and Europe (Collins, 2006; Zhang, Y. et al., 2008; Moore et al., 2009; Li et al., 2010; Pellicciotti et al., 2010; Stahl et al., 2010). Glacier runoff has decreased in the European Alps (Collins, 2006; Huss, 2011), in the central Andes of Chile (Casassa et al., 2009), and in the Cordillera Blanca (Baraer et al., 2012; *medium confidence*), a trend that has also been confirmed by qualitative observations made by local people (Bury et al., 2010; Carey et al., 2012a). For lake and river ice, there is generally *high confidence* in detection of, and a major role of climate change in, later freeze-up and earlier break-up over the past 100+ years for several sites in the NH, yet with regional differences and warmer regions showing higher sensitivities in interannual variability (Livingstone et al., 2010; Voigt et al., 2011; Weyhenmeyer et al., 2011; Benson et al., 2012). Changes in lake and river ice can have effects on freshwater ecosystems, transport and traffic over frozen lakes and rivers, and ice-induced floods during freeze-up and break-up events (Voigt et al., 2011). Some evidence exists in Europe that ice-jam floods were reduced during the last century due to reduced freshwater freezing (Svensson et al., 2006).

The rate of Arctic sea ice decline has increased significantly during the first decade of the 21st century, due to warming (WGI AR5 Section 4.2.2). It is *very likely* that at least some of the decline in Arctic sea ice extent can be attributed to anthropogenic climate forcing (WGI AR5 Section 10.5.1). Observations by Inuit people in the Canadian Arctic confirm with *high confidence* the instrumental observations on the various changes of sea ice (see Box 18-5). Antarctic sea ice has slightly increased over the past 30 years, yet with strong regional differences (WGI AR5 Section 4.2.3).

Combined *in situ* and satellite observations indicate a decline of 8% in NH spring snow cover extent since 1922 (WGI AR5 Section 4.5.2). A limited number of studies indicate an anthropogenic influence on snow cover reduction (*high confidence*; WGI AR5 Section 10.5.3), including a significant contribution of anthropogenic climate forcing on changes in snow pack and runoff timing between 1950 and 1999 in the western USA (Table 18-6; Barnett et al., 2008).

Climate change generally exerts a major role on permafrost changes. Widespread permafrost warming and thawing, and active layer thickening

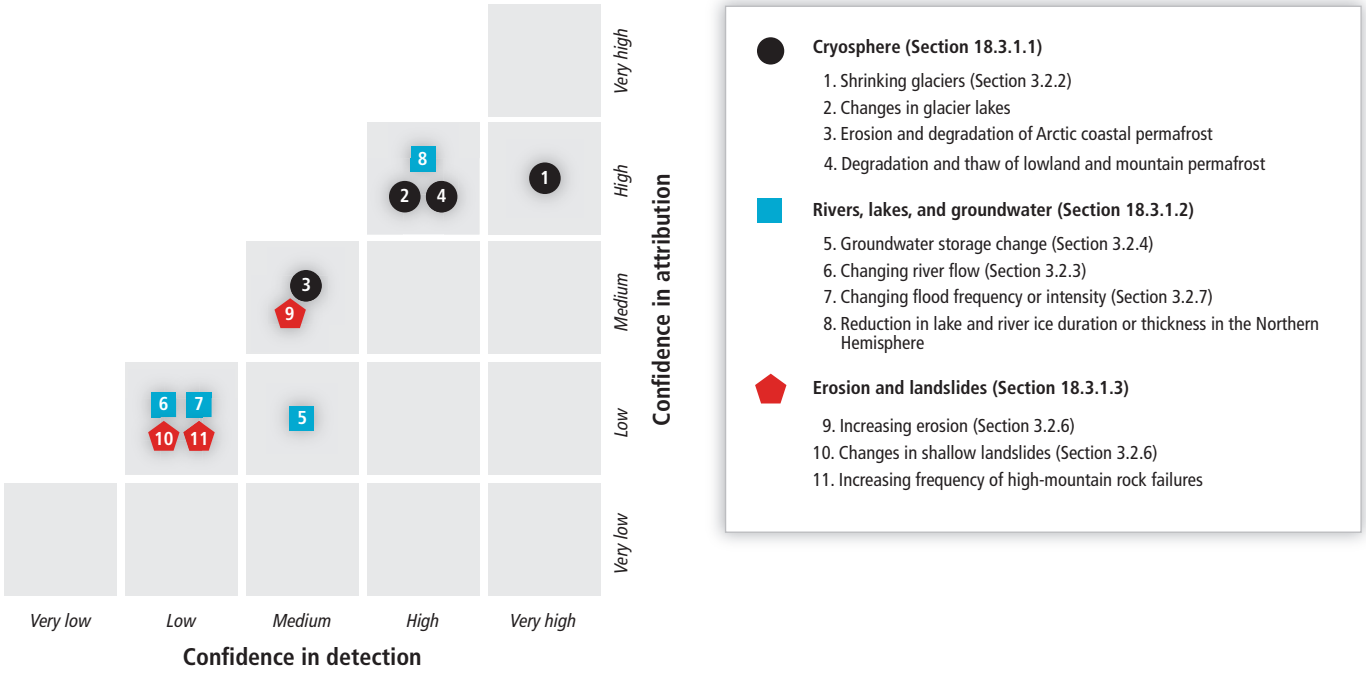


Figure 18-2 | Assessment of confidence in detection of observed climate change impacts in global freshwater systems over the past several decades, with confidence in attribution of a major role of climate change, based on expert assessment contained in Section 18.3.1 and augmented by subsections of Chapter 3 as indicated.

in both high-latitude lowlands and high-elevation mountain regions, have been observed over the past decades (*high confidence*; WGI AR5 Section 4.7.2). Climate change impacts have been related to permafrost changes, including an increase of flow speed of rock glaciers and debris lobes in the European Alps and Alaska (*high confidence*), resulting in rockfall, debris flows, and potential hazards to transport and energy systems (Kääb et al., 2007; Delaloye et al., 2010; Daanen et al., 2012), expansion, deepening and higher dynamics of thermokarst lakes and ponds in the Arctic (Rowland et al., 2010), and a doubled erosion rate of Alaska's northern coastline over the past 50 years (*high confidence*; Section 18.3.3.1, Table 18-8; Mars and Houseknecht, 2007; Karl et al., 2009; Forbes, 2011). Expansion of channel networks (Toniolo et al., 2009), increased river bank erosion (Costard et al., 2007), and an increase in hillslope erosion and landsliding in northern Alaska since the 1980s (Gooseff et al., 2009) have all been related to climate. Warming and thawing of permafrost in Alaska has adversely affected transport and energy structures and their operation (Karl et al., 2009). Feedbacks and interactions complicate detection of drivers and effects. For example, drying of land surface due to permafrost degradation may cause an increase in wildfires, in turn resulting in a loss of ground surface insulation and change in surface albedo that accelerates permafrost thawing (Rowland et al., 2010; Forkel et al., 2012).

18.3.1.2. The Regional Water Balance

The regional water balance is the net result of gains (precipitation, ice and snow melt, river inflow, and groundwater recharge) and losses (evapotranspiration, water use and river outflow, and groundwater discharge). Impacts of climate change include reduced availability of freshwater for use (one of the variables defining drought) or excess water (floods). Evapotranspiration, being a function of solar radiation, surface temperature, vegetation cover, soil moisture, and wind, is affected by the changing climate, but also by changing vegetation processes and land cover. At the global scale, human influence has contributed to large-scale changes in precipitation patterns over land and, since the mid-20th century, in extreme precipitation (*medium confidence*; WGI AR5 Section 10.6.1.2; Min et al., 2011). More locations worldwide have experienced an increase than a decrease in heavy rainfall events, yet with significant regional and seasonal variations (Seneviratne et al., 2012; Westra et al., 2013). In some regions, however, there is *medium confidence* that anthropogenic climate change has affected streamflow and evapotranspiration (WGI AR5 Section 10.3.2.3).

Change in river flow is a direct indicator of a changing regional water balance. Globally, about one-third of the top 200 rivers (ranked by river flow) show statistically significant trends during 1948–2004, with more rivers having reduced flow (45) than rivers with increased flow (Dai et al., 2009). Regional reductions in precipitation in southwestern South America are primarily due to internal variability (Dai, 2011; see also Section 27.2.1.1). River floods, defined as impacts caused by the over-topping of river banks and levées, have shown statistically significant increasing and decreasing trends in some regions. The role of climate change in these changes is uncertain, as they may reflect decadal climate variability and be affected by other confounding factors such as human alteration of river channels and land use (Section 3.2.7). In regions with detected increases in heavy rainfall events (North America, Europe), both increases and decreases in floods have been found (*medium confidence* in detection; Petrow and Merz, 2009; Villarini et al., 2009). In the UK, flood risk has increased due to anthropogenic forcing for events comparable to the 2000 floods (Kay et al., 2011; Pall et al., 2011; see also Section 18.4.3).

Expanding or new lakes as a result of ice melt at the margin of many shrinking glaciers in the Alps of Europe, Himalayas, Andes, and other mountain regions have altered the risk of glacier lake outburst floods (GLOFs) and required substantial risk reduction measures in the 21st century (Huggel et al., 2011; Carey et al., 2012b). Though there is no evidence for a change in frequency or magnitude of GLOFs (Seneviratne et al., 2012), climate change has had a major role in the substantial increase in glacial lake area in the eastern Himalaya region between 1990 and 2009 (Gardelle et al., 2011), and the similarly strong increase in lake numbers in the Andes of Peru in the second half of the 20th century (Carey, 2005), and in northern Patagonia from 1945 to 2011 (Loriaux and Casassa, 2013; *high confidence* in detection). New glacier lakes are not only an additional source of floods but also have become a tourist attraction, led to additional infrastructure, and stimulated assessment of potential for hydropower generation (Terrier et al., 2011).

Since the 1950s some regions of the world have experienced more intense and longer droughts, although a global trend currently cannot be established (Seneviratne et al., 2012; see also Section 3.2.2 and WGI AR5 Section 2.6.2.3). Longer drought periods have affected groundwater recharge (Leblanc et al., 2009; Taylor et al., 2013), but changes in groundwater storage are generally difficult to attribute to climate change, due to confounding factors from human activities (Table 3-1; Rodell et al., 2009; Taylor et al., 2013). Likewise, confounding factors do not permit attribution of observed changes in water quality to climate change (Kundzewicz and Krysanova, 2010; see also Section 3.2.5).

18.3.1.3. Erosion, Landslides, and Avalanches

Erosion and landsliding typically increase in phase with deglaciation in mountain areas (Ballantyne, 2002; Korup et al., 2012), and there is emerging evidence for this to occur during contemporary deglaciation (Schneider et al., 2011; Uhlmann et al., 2013). In the western Himalaya, sediment flux has increased (*medium confidence*; Wulf et al., 2012) and been related to hydrologic extreme events over the past 60 years (*low confidence*; Malik et al., 2011), with important consequences for hydropower schemes. In China, a drastic decrease of sediment load in the Yangtze River was observed since the 1980s. There have been local variations in precipitation and runoff since 1950, but changes in sediment load are attributed primarily to more than 50,000 dams and vegetation changes (*medium confidence*; Xu et al., 2008). There is clear evidence for decline in sediment load in the Zhujiang (Pearl River) basin since the early 1990s (Zhang, S. et al., 2008).

In the European Alps, no clear evidence exists so far for any change in frequency of shallow landslides and debris flows from recently deglaciated mountain areas (Jomelli et al., 2004; Stoffel and Huggel, 2012). In some cases climate change has had a major role in influencing frequency and magnitude of alpine shallow landslides and debris flows

by altering sediment yield, for example, from rockfall or disintegration of rock glaciers (*low confidence*; Lugon and Stoffel, 2010).

Glacier shrinkage, permafrost degradation, and high-temperature events have contributed to many high-mountain rock slope failures since the 1990s (*medium confidence* in major role of climate change; Allen et al., 2010; Ravanel and Deline, 2011; Schneider et al., 2011; Fischer et al., 2012; Huggel et al., 2012a). Rock slope failures have increased over this period in the Western Alps of Europe (*high confidence*), the New Zealand Alps (*medium confidence*), and globally (*low confidence*). Cascading processes of permafrost and ice-related landslides impacting lakes and downstream areas have been observed in many high-mountain regions, causing major damages and risk reduction measures (*high confidence*), with climate change exerting a major role (*medium confidence*; e.g., Xin et al., 2008; Bajracharya and Mool, 2009; Künzler et al., 2010; Carey et al., 2012a; Huggel et al., 2012b). For landslide types other than the above, there is no clear evidence that their frequency or magnitude has changed over the past decades (Huggel et al., 2012b). In general, detection of changes in the occurrence of landslides is complicated by incomplete inventories, both in time and space, and inconsistency in terminology.

Physical understanding suggests that climate change has a major role in changes of snow avalanche activity but no such changes have been reported so far (*medium confidence*; Laternser and Schneebeli, 2002; Voigt et al., 2011), except for the French Alps (Eckert et al., 2013; *medium confidence* in detection). The detection of changes in snow avalanche impacts, such as fatalities and property loss, is difficult over the past decades because of changes in snow sport activities and avalanche defense measures.

18.3.2. Terrestrial and Inland Water Systems

As documented by previous IPCC reports (notably Rosenzweig et al., 2007), climate-driven changes in terrestrial and inland water systems are widespread and numerous. Confidence in such detection of change is often *very high*, reflecting *high agreement* among many independent sources of evidence of change, and *robust evidence* that changes in ecosystems or species are outside of their natural variation. Confidence in attribution to climate change is also often *high*, due to process understanding of responses to climate change, or strong correlations with climate trends and where confounding factors are understood to have limited importance (Sections 4.3.2, 4.3.3, Figure 4-4). The scientific literature in this field is growing quickly; detailed traceability is provided in Chapter 4.

Organisms respond to changing climate in a multitude of ways, including through their phenology (the timing of key life history events such as flowering in plants or migration of birds), productivity (the assimilation of carbon and nutrients in biomass), spatial distribution, mortality/extinction, or by invading new territory. Noticeable changes may occur at the level of individual organisms, ecosystems, landscapes, or by modification of entire biomes. Organisms and ecosystems are adapted to a variable environment, and they are capable of adapting to gradual change to some degree. Assessing confidence in the detection of such change therefore involves assumptions about natural variability in these ecosystems, while assessment of confidence in the attribution of detected change to climate drivers (or carbon dioxide (CO_2)) implies the assessment of confounding drivers such as pollution or land use change.

18.3.2.1. Phenology

Since the AR4 there has been a further substantial increase in observations, showing that hundreds of (but not all) species of plants and animals have changed functioning to some degree over the last decades to centuries on all continents (*high confidence* due to *robust evidence* but only *medium agreement* across all species; Section 4.3.2.1; Menzel et al., 2006; Cook et al., 2012b; Peñuelas et al., 2013). New satellite-based analyses confirm earlier trends, showing, for example, that the onset of the growing season in the NH has advanced by 5.4 days from 1982 to 2008 and its end has been delayed by 6.6 days (Jeong et al., 2011). Significant changes have been detected, by direct observation, for many different species, for example, for amphibians (e.g., Phillimore et al., 2010), birds (e.g., Pulido, 2007; Devictor et al., 2008), mammals (e.g., Adamík and Král, 2008), vascular plants (e.g., Cook et al., 2012a), freshwater plankton (Adrian et al., 2009), and others (Section 4.3.2.1); a number of new meta-analyses have been carried out summarizing this literature (e.g., Cook et al., 2012a). Attribution of these changes to climate change is supported by more refined analyses that consider also the regional changes in several variables such as temperature, growing season length, precipitation, snow cover duration, and others, as well as experimental evidence (Xu et al., 2013). The *high confidence* in attributing many observed changes in phenology to changing climate is a result of these analyses, as well as of improved knowledge of confounding factors such as land use and land management (see also Section 4.3.2.1).

18.3.2.2. Productivity and Biomass

Many terrestrial ecosystems are now net sinks for carbon over much of the NH and also in parts of the Southern Hemisphere (*high confidence*; see also Sections 4.3.2.2-3). This is shown, for example, by inference from atmospheric chemistry, but also by direct observations of increased tree growth in many regions including Europe, the USA, tropical Africa, and the Amazon. During the decade 2000 to 2009, global land net primary productivity was approximately 5% above the preindustrial level, contributing to a net carbon sink on land of 2.6 ± 1.2 PgC yr^{-1} (Section 4.3.2.2; WGI AR5 6.3.2.6; for primary literature, see also Raupach et al., 2008; Le Quéré et al., 2009), despite ongoing deforestation. Forests have increased in biomass for several decades in Europe (Luyssaert et al., 2010) and the USA (Birdsey et al., 2006). These trends are in part due to nitrogen deposition, afforestation, and altered land management which makes direct attribution of the increase to climate change difficult. The degree to which rising atmospheric CO_2 concentrations contribute to this trend remains a particularly important source of uncertainty (Raupach et al., 2008). Canadian managed forests increased in biomass only slightly during 1998-2008, because growth was offset by significant losses due to fires and beetle outbreaks (Stinson et al., 2011). In the Amazon forest biomass has generally increased in recent decades, dropping temporarily after a drought in 2005 (Phillips et al., 2009). A global analysis of long-term measurements suggests that soil respiration has increased over the past 2 decades by approximately

0.1 PgC yr^{-1}, some of which may be due to increased productivity (Bond-Lamberty and Thomson, 2010). Man-made impoundments in freshwater ecosystems represent an increasing and short-lived additional carbon store with conservative annual estimates of 0.16 to 0.2 PgC yr^{-1} (Cole et al., 2007).

18.3.2.3. Species Distributions and Biodiversity

Each species responds differently to a changing environment; therefore the composition of species, genotypes, communities, and even ecosystems varies in different ways from place to place, in response to climate change. The consequences are changing ranges of species, changing composition of the local species pool, invasions, mortality, and ultimately extinctions. For different species and species groups, detected range shifts vary, and so do the confidence of detection and the degree of attribution to climate change. The number of species studied has considerably increased since the AR4. Overall, many terrestrial species have recently moved, on a global average, 17 km poleward and 11 m up in altitude per decade (e.g., Europe, North America, Chile, Malaysia), which corresponds to predicted range shifts due to warming (Chen, I.C. et al., 2011) and is two to three times faster than previous estimates (Parmesan and Yohe, 2003; Fischlin et al., 2007), with *high confidence* in detection. Europe forest species are moving up in altitude, probably due to climate warming at the end of the 20th century (Gehrig-Fasel et al., 2007; Lenoir et al., 2008). Species with short life cycles and high dispersal capacity—such as butterflies (*high confidence* in a major role of climate change)—are generally tracking climate more closely than longer-lived species or those with more limited dispersal such as trees (Devictor et al., 2012; *medium confidence* in a major role of climate change). There are many less well-studied species for which detection of change and its attribution to climate change are more uncertain.

Changes in abundance, as measured by changes in the population size of individual species or shifts in community structure within existing range limits, have occurred in response to recent global warming (Thaxter et al., 2010; Bertrand et al., 2011; Naito and Cairns, 2011; Rubidge et al., 2011; Devictor et al., 2012; Tingley et al., 2012; Vadadi-Fülöp et al., 2012; Cahill et al., 2013; Ruiz-Labourdette et al., 2013), but owing to confounders, confidence in a major role of climate change is often *low*. Across the world, species extinctions are at or above the highest rates of species extinction in the fossil record (*high confidence*; Barnosky et al., 2011). However, only a small fraction of observed species extinctions have been attributed to climate change—most have been ascribed to non-climatic factors such as invasive species, overexploitation, or habitat loss (Cahill et al., 2013). For those species where climate change has been invoked as a causal factor in extinction (such as for the case of Central American amphibians), there is *low agreement* among investigators concerning the importance of climate variation in driving extinction and even less agreement that extinctions were caused by climate change (Pounds et al., 2006; Kiesecker, 2011). Confidence in the suggested attribution of extinctions across all species to climate change is *very low* (see also Section 4.3.2.5).

Species invasions have increased over the last several decades worldwide, notably in freshwater ecosystems (*very high confidence*), often causing biodiversity loss or other negative impacts. There is only *low confidence* that species invasions have generally been assisted by recent climatic trends because of the overwhelming importance of human facilitated (intentional or non-intentional) dispersal in the transfer from the area of origin. Once established in a new environment, many introduced species have recently become invasive due to climate change (*medium* to *high confidence*, depending on the taxon; see also Section 4.2.4.6).

18.3.2.4. Impacts on Major Systems

Field and satellite measurements indicate substantial changes in freshwater and terrestrial ecosystems (often linked to permafrost thawing) in many areas of the Arctic tundra (*high confidence*; Hinzman et al., 2005; Axford et al., 2009; Jia et al., 2009; Post et al., 2009; Prowse and Brown, 2010; Myers-Smith et al., 2011; Walker et al., 2012). Vegetation productivity has systematically increased over the past few decades in both North America and northern Eurasia (Goetz et al., 2007; Jia et al., 2009; Elmendorf et al., 2012). Most subpopulations of the polar bear are declining in number (Vongraven and Richardson, 2011). These changes correspond to expectations, based on experiments, models, and paleoecological responses to past warming, of broad-scale boreal forest encroachment into tundra, a process that takes decades and that would have very large impacts on ecosystem structure and function. The particular strength of warming over the last 50 years for most of the Arctic further facilitates attribution of a major role of climate change (*high confidence*). The change affects a significant area of the tundra biome and can be considered an early warning for an ongoing regime shift (Section 4.3.3.4, Figure 4-4).

For the boreal forest, increases in tree mortality are observed in many regions, including widespread dieback related to insect infestations and/or fire disturbances in North America (Fauria and Johnson, 2008; Girardin and Mudelsee, 2008; Kasischke et al., 2010; Turetsky et al., 2010; Wolken et al., 2011) and in Siberia (Soja et al., 2007), but there is *low confidence* in detection of a global trend. Many areas of boreal forest have experienced productivity declines (*high confidence*; Goetz et al., 2007; Parent and Verbyla, 2010; Beck and Goetz, 2011), related to warming-induced drought, specifically the greater drying power of air (Williams et al., 2012), inducing photosynthetic down-regulation of boreal tree species not adapted to the warmer conditions (Welp et al., 2007; Bonan, 2008). Conversely, productivity has increased along the boreal-tundra ecotone where more mesic (moist) conditions may be generating the expected warming-induced positive growth response (McGuire et al., 2007; Goldblum and Rigg, 2010; Beck and Goetz, 2011). Overall, these multiple impacts in the boreal forest biome can be considered an early warning for an ongoing regime shift only with *low confidence* (Section 4.3.3.1.1, Figure 4-4). Many of the aforementioned changes take place in the tundra-boreal ecotone, affecting both biomes significantly (Box 4-4, Figure 4-10).

In tropical forests, climate change effects are difficult to identify against the confounding effects of direct human influence as is well illustrated for the Amazon forest (Davidson et al., 2012) but also applies elsewhere. Since AR4, there is new evidence of more frequent severe drought episodes in the Amazon region that are associated with observed sea

surface temperature increases in the tropical North Atlantic (*medium confidence*; Marengo et al., 2011a). There is *low confidence*, however, that these changes can be attributed to climate change (Section 4.3.3.1.3). There is *medium confidence* that tree mortality in the Amazon region has increased due to severe drought and increased forest fire occurrence and *low confidence* that this can be attributed to warming (Section 4.3.3.1.3, Figures 4-4, 4-8).

In freshwater ecosystems of most continents and climate zones, rising temperatures have been linked to shifts in invertebrate and fish community composition, especially in headwater streams where species are more sensitive to warming (Brown et al., 2007; Durance and Ormerod, 2007; Chessman, 2009; see also Section 4.3.3.3; *high confidence* in detection, *low confidence* in a major role of climate change due to numerous confounding factors). Long-term shifts in macroinvertebrate communities have been observed in European lakes where temperatures have increased (Burgmer et al., 2007).

18.3.3. Coastal Systems and Low-Lying Areas

Coastal systems are influenced by many anthropogenic and natural processes. Important climate-related drivers include changes in ocean temperature, salinity, and pH; and sea level (see Table 5-2). In coastal waters, both annual and seasonal changes in temperature tend to be larger than the average rate for the open ocean (Section 5.3.3). Sea surface temperatures have increased significantly during the past 30 years along more than 70% of the world's coastlines, with large spatial and seasonal variation, and the frequency of extreme temperature events in coastal waters has changed in many areas (Lima and Wethey, 2012). Seawater pH spans larger ranges and exhibits higher variability near coastlines, and anthropogenic ocean acidification can be enhanced or reduced by coastal geochemical processes (Borges and Gypens, 2010; Feely et al., 2010; Duarte et al., 2013, see also Box CC-OA).

While it is likely that extreme sea levels have increased globally since the 1970s, mainly as a result of mean sea level rise due in part to anthropogenic warming (WGI AR5 Sections 3.7.5-6, 10.4.3), local sea level trends are also influenced by factors such as regional variability in ocean and atmospheric circulation, subsidence, isostatic adjustment, coastal erosion, and coastal modification (see also Section 5.3.2). As a consequence, the detection of the impact of climate change in observed changes in relative sea level remains challenging (Nicholls et al., 2007, 2009; Menéndez and Woodworth, 2010). An exception is lower sea level in regions of isostatic rebound in response to reduced ice cover due to climate change (Kopp et al., 2010; Tamisiea and Mitrovica, 2011). In these regions, climate change has played a major role in the lowering sea level (*medium confidence*).

18.3.3.1. Shoreline Erosion and Other Coastal Processes

Throughout the world, the rate of shoreline erosion is increasing (Section 5.4.2.1). While processes related to climate change, such as rising mean sea levels (Leatherman et al., 2000; Ranasinghe and Stive, 2009), more frequent extreme sea levels (Woodworth et al., 2011), or permafrost degradation and sea ice retreat (Forbes, 2011) can be expected to enhance global erosion, there are multiple drivers involved in shoreline erosion that are unrelated to climate change including long shore sediment transport; the diversion of sediments by dams; and subsidence due to resource extraction, mining, and coastal engineering and development (see also Table 5-3). Owing to the fragmentary nature of the information available, and to the multiple natural and anthropogenic stressors contributing to coastal erosion, confidence in detection of a climate change contribution to observed shoreline changes is *very low*, with the exception of polar regions (Table 18-8; Mars and Houseknecht, 2007; Forbes, 2011).

Coastal lagoons and estuaries, as well as deltas, are highly susceptible to alterations of sediment input and accumulation (Syvitski et al., 2005; Ravens et al., 2009), processes that can be influenced by climate change via changes in mean and extreme sea levels, storminess, and precipitation. However, the primary drivers of widespread observed changes in those systems are human drivers other than climate change so that there is *very low confidence* in the detection of impacts related to climate change (Section 5.4.2).

Coastal aquifers are crucial for the water supply of densely populated coastal areas, in particular in small island environments and dry climates. Aquifer recharge is sensitive to changes in temperature and precipitation, and rising sea levels and saltwater overwash from storm surges can contribute to saline intrusion into groundwater (Post and Abarca, 2010; Terry and Falkland, 2010; White and Falkland, 2010; see also Section 29.3.2, Table 18-8). However, groundwater extraction for coastal settlements and agriculture is the main cause for widely observed groundwater degradation in coastal aquifers (e.g., White et al., 2007a; Barlow and Reichard, 2010). It is not yet possible to detect the impact of climate change on coastal aquifers with any degree of confidence (Rozell and Wong, 2010; White and Falkland, 2010).

Changes in water column mixing have combined with other factors such as nutrient loading to drive down oxygen concentrations and increase the number and extent of hypoxic zones (Vaquer-Sunyer and Duarte, 2011). These zones are characterized by very low oxygen and high CO_2 levels and, in some cases, exert strong local and regional effects on marine biota such as distribution shifts, habitat contraction or loss, and fish kills (Diaz and Rosenberg, 2008). The operation of other factors makes the detection of a climate change impact on the frequency, distribution, and intensity of hypoxia possible with only *medium confidence* and it is difficult to assess the relative magnitude of this impact (see Table 18-1).

18.3.3.2. Coastal Ecosystems

Coastal habitats and ecosystems experience cumulative impacts of land- and ocean-based anthropogenic stressors (Halpern et al., 2008). Most coral reefs, seagrass beds, mangroves, rocky reefs, and shelves have undergone substantial changes over the course of the last century. Fishing and other extractive activities, land use changes, and pollution have been responsible for a large proportion of these historical changes (Lotze et al., 2006). Biological responses to changes in the temperature, chemistry, and circulation of the ocean are complex and often interact with other anthropogenic factors.

Box 18-2 | Attribution of Mass Coral Bleaching Events to Climate Change

A critical source of energy for the maintenance and growth of coral is provided by symbiotic brown algae. Coral bleaching occurs when these symbionts leave their host. Bleaching events have deleterious impacts on corals and, depending on their severity and duration, can cause death. It is known that thermal stress can trigger coral bleaching (Muscatine, 1986; Hoegh-Guldberg and Smith, 1989; Jones et al., 1998). Mass bleaching events that affect entire reefs or coastal regions can occur when local or regional temperatures exceed the typical summer maximum for a period of a few weeks (Hoegh-Guldberg, 1999; Baker et al., 2008; Strong et al., 2011). The effect of elevated temperature is exacerbated by strong solar irradiance (Hoegh-Guldberg, 1999).

Since 1980, mass coral bleaching events have occurred throughout the tropics and subtropics at a rate without precedent in the literature (see also Boxes CC-CR and CC-OA, and Section 5.4.2.4). These events have often been followed by mass mortality (Hoegh-Guldberg, 1999; Baker et al., 2008). In the very warm year of 1998, for example, mass bleaching occurred in almost every part of the tropics and subtropics and resulted in the loss of a substantial fraction of the world's corals (Wilkinson et al., 1999). A large-scale bleaching event also occurred in the Caribbean during 2005 (Eakin et al., 2010).

Declining water quality, coastal development, increased fishing, and even tourism have also been implicated in the decline of coral communities over the past 50 years (Bryant et al., 1998; Gardner et al., 2003; Bruno and Selig, 2007; Sheppard et al., 2010; Burke et al., 2011; De'ath et al., 2012). However, given the scope of recent mass bleaching events, their co-occurrence with elevated temperatures, and a physiological understanding of the role of temperature in bleaching, there is *very high confidence* in the detection of the impact of climate change and *high confidence* in the finding that climate change has played a major role.

Coral reefs have been degraded due both to local anthropogenic factors such as fishing, land use changes, and pollution and to ocean warming related to climate change and also possibly to acidification (see Box CC-CR). Over the past 30 years, mass coral bleaching has been detected with *very high confidence* on all coasts, and warming is a major contributor (*high confidence*; for further discussion see Boxes 18-2, CC-OA).

Changes in abundance and distribution of rocky shore species have been observed since the late 1940s in the Northeast Atlantic (Hawkins et al., 2008), and the role of temperature has been demonstrated by experiments and modelling (Poloczanska et al., 2008; Wethey and Woodin, 2008; Peck et al., 2009; Somero, 2012; see also Section 5.4.2.2). Globally, the ranges of many rocky shore species have shifted up to 50 km per decade, much faster than most recorded shifts of terrestrial species (Helmuth et al., 2006; Poloczanska et al., 2013; see also Box 18-3). However, distinguishing the response of these communities to climate change from those due to other natural and anthropogenic causes is challenging. Weak warming, overriding effects of confounding factors, or biogeographic barriers can explain the fact that geographical distribution of some species did not change over the past decades (Helmuth et al., 2002, 2006; Rivadeneira and Fernández, 2005; Poloczanska et al., 2011).

Ocean warming has contributed to observed range shifts in vegetated coastal habitats such as coastal wetlands, mangrove forests and seagrass meadows (Section 5.4.2.3). Poleward expansion of mangrove forests, consistent with expected behavior under climate change, has been observed in the Gulf of Mexico (Perry and Mendelssohn, 2009; Comeaux et al., 2012; Raabe et al., 2012) and New Zealand (Stokes et al., 2010). High temperatures have impacted seagrass biomass in the Atlantic Ocean (Reusch et al., 2005; Díez et al., 2012; Lamela-Silvarrey et al., 2012), the Mediterranean Sea (Marbà and Duarte, 2010), and Australian waters (Rasheed and Unsworth, 2011). Extreme weather events also contributed to the overall degradation of seagrass meadows in a Portuguese estuary (Cardoso et al., 2008).

Decline in kelp populations attributed to ocean warming has occurred off the north coast of Spain (Fernández, 2011), as well as in southern Australia, where the poleward range expansion of some herbivores have also contributed to observed kelp decline (Ling, 2008; Ling et al., 2009a,b; Johnson et al., 2011; Wernberg et al., 2011a). The spread of subtropical invasive macroalgal species (e.g., Lima et al., 2007) may be adding to the stresses temperate seagrass meadows experience from ocean warming. Extreme temperature events can alter marine and coastal communities, as shown, for example, for the European 2003 heat wave (Garrabou et al., 2009), and the early 2011 heat wave off the Australian west coast (Wernberg et al., 2012).

In summary, there is *high confidence* in the detection of the impact of climate change on the abundance and distribution of a range of coastal species and *medium confidence* that climate change has played a major role in many cases. In specific cases, such as the decline of salt marshes and mangroves, the impact of climate change has been detected with *very low confidence* owing to the overriding effect of land use changes, pollution, and other factors unrelated to climate change.

18.3.3.3. Coastal Settlements and Infrastructure

Total damages from coastal flooding have increased globally over the last decades (*high confidence*); however, with exposure and subsidence constituting the major drivers, confidence in detection of a climate change impact is *very low* (Seneviratne et al., 2012, see also Sections 5.4.3.2, 5.4.4).

Recent global (e.g., Menéndez and Woodworth, 2010; Woodworth et al., 2011) and regional (e.g., Marcos et al., 2009; Haigh et al., 2010, 2011) studies have found increases in extreme sea levels consistent with mean sea level trends (see also Table 5-2), indicating that the increasing frequency of extreme water levels affecting coastal infrastructures observed so far is related to rising mean sea level rather than to changes in the behavior of severe storms. While vulnerability of coastal settlements and infrastructure to future climate change, in particular sea level rise and coastal flooding, is widely accepted and well documented (see Section 5.5), there is a shortage of studies discussing the role of climate change in observed impacts on coastal systems.

Increases in saltwater intrusion and flooding have been observed in low-lying agricultural areas of deltaic regions and small islands, but the contribution of climate change to this is not clear (e.g., Rahman et al., 2011; see also Sections 5.4.2.5, 5.4.3.3). While both climate change impacts on physiological and ecological properties of fish (e.g., Barange and Perry, 2009; see also Section 18.3.4) and vulnerability of coastal communities and fisherfolks to climate fluctuations and change (Badjeck et al., 2010; Cinner et al., 2012) are well established in the literature, there is *limited evidence* for observed effects of climate change on coastal fishery operations (see also Section 18.4.1.2).

18.3.4. Oceans

Since 1970, ocean temperatures have increased by around 0.1°C per decade in the upper 75 m and approximately 0.015°C per decade at 700 m (see Section 30.3.1.1). It is *very likely* that the increase in global ocean heat content observed in the upper 700 m since the 1970s has a substantial contribution from anthropogenic forcing (WGI AR5 Section 10.4.1).

The increased flux of CO_2 from the atmosphere to the ocean has reduced the average pH of sea water by about 0.1 pH units over the past century, with the greatest reduction occurring at high latitudes (see also Box CC-OA). These changes have been attributed to increases in the atmospheric concentration of greenhouse gases as result of human activities (*very high confidence*; WGI AR5 Section 10.4.4). Changes in wind speed, upwelling, water column stratification, surface salinity, ocean currents, and oxygen depth profile have also been been detected with at least *medium confidence* (WGI AR5 Chapter 3; Figures 30-5, 30-6).

Changes in the physical and chemical nature of ocean environments are predicted to have impacts on marine organisms and ecosystems, with many already having been observed across most ocean regions (Sections 6.2-3, 30.4-5). However, the detection of these predicted changes and the assessment of the role of climate change in them are complicated by the influence of long-term variability such as the Pacific Decadal Oscillation (PDO) and the Atlantic Multi-decadal Oscillation (AMO). The fragmentary nature of ocean observations and the influence of confounding factors such as fishing, habitat alteration, and pollution also represent significant challenges to detection and attribution (Hoegh-Guldberg et al., 2011; Parmesan et al., 2011; see also Box 18-3).

Table 18-1 | Observed changes in ocean system properties and their effects, with confidence levels for the detection of the effect of climate change and an assessment of the magnitude of its role.

Process	Confidence in		Role	Context	Reference
	Detection	Attribution			
Impacts of ocean acidification on pelagic marine biota	*Low*	*Very low*	Minor	For example, reduction in foraminiferan, coccolithophores, and pteropod shell weight. Attribution supported by experimental evidence and physiological knowledge.	1
Expansion of midwater hypoxic zones	*Medium*	*Low*	Minor	Oxygen minimum zones caused by enhanced stratification and bacterial respiration due to effects of warming	2
Regional and local impacts of expanding hypoxic zones	*Medium*	*Low*	Minor	Reduction of biodiversity, compression of oxygenated habitat for intolerant species, range expansion for tolerant taxa	3
Direct temperature effects on marine biota related to limited physiological tolerance ranges	*Very high*	*High*	Major	For example, large-scale latitudinal shifts of species distribution, changes in community composition; attribution supported by experimental and statistical evidence as well as physiological knowledge	4
Increase in net primary production at high latitudes	*Medium*	*Medium*	Major	At higher latitudes, net primary production is increasing owing to sea ice decline and warming. At the global scale, estimates vary regionally, and there is a discrepancy between satellite observations and open ocean time series sites.	5
Changes in microbial processes	*Low*	*Very low*	Minor	Limited understanding of microbial processes, drivers, and interactions, and subsequently of large-scale shifts in biogeochemical pathways such as oxygen production, carbon sequestration, and export production and nitrogen fixation	6

Key references and further related information for the assessment in this table:
[1]Wootton et al. (2008); De Moel et al. (2009); Moy et al. (2009); Bednaršek et al. (2012); Section 6.3.2; Box CC-OA
[2]Stramma et al. (2008); Stolper et al. (2010); Sections 6.1.1.3 and 6.3.3
[3]Levin et al. (2009); Ekau et al. (2010); Stramma et al. (2010, 2012); Sections 6.3.3, 6.3.5, and 30.5
[4]Merico et al. (2004); Perry et al. (2005); Pörtner and Farrell (2008); Beaugrand et al. (2010); Alheit et al. (2012); Section 6.3.1
[5]Behrenfeld et al. (2006); Saba et al. (2010); Arrigo and Van Dijken (2011); Section 6.3.4; Box CC-PP
[6]Sections 6.3.1.2, 6.3.2.2, 6.3.3.2, and 6.3.5.2

18.3.4.1. Impacts on Ocean System Properties and Marine Organisms and Ecosystems

Greater thermal stratification in many regions has reduced ocean ventilation and mixing depth. As this reduces the availability of inorganic nutrients, it can reduce primary productivity in surface layers. However, trends in primary production from different observational methods disagree (Sections 6.1.1, 6.3.4; Box CC-PP). Coastal upwelling has increased in some regions bringing greater concentrations of nutrients to surface waters, boosting productivity and enhancing fisheries output (see Section 30.5.5). Increases in productivity also occurred with warming and sea ice loss at high latitude (*medium confidence*; Table 18-1).

Poleward shifts in the distributions of zooplankton, fish, seabirds, and benthic invertebrates related to climate change have been detected with *high confidence* in the well-studied Northeast Atlantic. There is also *high confidence* that climate change has played a *major role* in these shifts (Box 6-1; Sections 6.3, 30.5.1). In many regions, temperature exerts the strongest influence on ecosystems and the responses of ecological systems to changing temperature are well studied. However, it is often difficult to clearly identify the interaction of temperature with other factors (Section 6.3.5). Some studies have found changes in the abundance of fish species that are consistent with regional warming, with differences in response between species, in line with differential specializations of coexisting species (Sections 6.2, 6.3.1; see also Pörtner, 2012). Anthropogenic influences modulate responses to climate, for example, due to exploitation status (Tasker, 2008; Belkin, 2009; Overland et al., 2010; Schwing et al., 2010), with more heavily exploited species being more sensitive to environmental variability in general, including temperature trends and extremes (Hsieh et al., 2005, 2008; Stige et al., 2006).

Laboratory experiments have shown that a broad range of marine organisms (e.g., corals, fish, pteropods, coccolithophores, and macroalgae), physiological processes (e.g., skeleton formation, gas exchange, reproduction, growth, and neural function), and ecosystems processes (e.g., productivity, reef building, and erosion) are sensitive to changes in pH and carbonate chemistry of seawater (Section 6.2, Box CC-OA). However, few field studies have been able to detect specific changes in marine ecosystems to ocean acidification owing to the inability to identify the effect of ocean acidification from ocean warming or local factors (Wootton et al., 2008; De Moel et al., 2009; Moy et al., 2009; Bednaršek et al., 2012; see also Section 6.3.2).

There has been a substantial increase in the number of studies documenting significant changes in marine species and processes since the AR4. A new meta-analysis using a database of long-term observations from peer-reviewed studies of biological systems, with nearly half of the time series extending prior to 1960, shows that more than 80% of observed responses are consistent with regional climate change (see Section 30.4, Box CC-MB). Poloczanska et al. (2013) argue that the high consistency of marine species' responses across geographic regions (coastal to open ocean, polar to tropical), taxonomic groups (phytoplankton to top predators), and types of responses (distribution, phenology, abundance) reported in their analysis support the detection of a widespread impact of climate change on marine populations and ecosystems (see Sections 30.4 and 30.5 for more detail). Table 18-2 gives examples of the manifestation of climate change on marine species and ecosystems.

18.3.4.2. Observed Climate Change Effects across Ocean Regions

Climate change has affected physical properties across the ocean, with regional variations (Table 30-1; Figures 30-2 to 30-5; WGI AR5 Chapter 3). Confidence in the detection and attribution of these impacts also varies regionally, reflecting differences in system understanding, data availability, influence of long-term natural variability, and the impact of factors unrelated to climate change. The attribution of changes in heat content to climate change is less certain regionally than globally, but warming has been detected with *high confidence* in all basins except

Table 18-2 | Observed changes in marine species and ecosystems, with confidence levels for the detection of the effect of climate change and an assessment of the magnitude of its role (see also Sections 6.2, 6.3, and 30.4; Box CC-MB).

Process	Confidence in		Role	Context	Reference
	Detection	Attribution			
Range shifts of fish and macroalgae	*High*	*High*	Major	Changes in species biogeographical ranges to higher latitudes or greater depths	1
Changes in community composition	*High*	*High*	Major	Due to effects of warming, hypoxia, and sea ice retreat	1
Changes in abundance	*High*	*Medium*	Major	Observed in fish, corals, and intertidal species	1
Impacts on large non-fish species, e.g., walruses, penguins, and other sea birds	*High*	*High*	Major	Observed effects include changing abundance, phenology, species distribution and turtle sex ratios, and are mediated mostly through changes in resource availability, including prey.	2
Impacts on reef-building corals	*Very high*	*High*	Major	Effects attributed mostly to warming and rising extreme temperatures, though ocean acidification may contribute	3
Changes in fish species richness in temperate and high-latitude zones	*High*	*Medium*	Major	Effect associated with loss of sea ice and latitudinal species shifts due to warming trends	4

Key references and further related information for the assessment in this table:
[1]Müller et al. (2009); Stige et al. (2010); Sections 6.3.1 and 30.4; Box CC-MB
[2]Grémillet and Boulinier (2009); McIntyre et al. (2011); Section 6.3.7
[3]Hoegh-Guldberg (1999); Hoegh-Guldberg et al. (2007); Baker et al. (2008); Veron et al. (2009); Sections 6.3.1.4 and 6.3.1.5; Box CC-CR
[4]Hiddink and ter Hofstede, (2008); Beaugrand et al. (2010); Box 6-1; Section 6.3.1.5

Box 18-3 | Differences in Detection and Attribution of Ecosystem Change on Land and in the Ocean

Marine and terrestrial ecosystems differ in fundamental ways. Gradients in turbulence, light, pressure, and nutrients uniquely drive fundamental characteristics of organisms and ecosystems in the ocean. While the critical factor for transporting nutrients to marine primary producers is ocean mixing driven by wind, water is the primary mode for transporting nutrients to land plants. In addition to these characteristics, marine ecosystems are often more technically difficult and costly to explore than terrestrial equivalents, which explains the low number and shorter scientific studies of marine ecosystems (Hoegh-Guldberg and Bruno, 2010). The latter has restricted the extent to which changes within the ocean can be detected and attributed.

Impacts of climate change in terrestrial and marine systems differ significantly for the same types of measures, for example, species phenology and range shifts, leading to differences in experts' interpretations of the data and possibly divergent levels of confidence in detection and attribution. There are also fundamental differences in exposure of organisms to recent warming, their biological responses, and our ability to detect change through observations. Changes in temperature of ocean systems have generally been less than those of terrestrial ecosystems over the last 4 decades (Burrows et al., 2011). Furthermore, despite higher variability the horizontal spatial gradient of temperature change (°C km^{-1}) is generally much higher in terrestrial ecosystems than in marine ecosystems. All else being equal, the net result is that species have generally needed to move much shorter distances in terrestrial ecosystems to stay within their preferred climates, also due to the influence of the topography such as mountain ranges (Burrows et al., 2011), although many marine species can potentially exploit strong vertical thermal gradients to attenuate the need for range shifts in response to warming.

Species and ecosystems may respond very differently to these climate signals in ways that influence the ability to detect change. For example, a comparison of ectotherm species (i.e., species that do not actively regulate their body temperatures, such as reptiles and fish) indicates that marine species' ranges have tracked recent warming at both their poleward and equatorial range limits, while many terrestrial species' ranges have tracked warming only at their poleward range limits (Sunday et al., 2012). Biological processes influencing phenological shifts may also differ substantially between systems. For example, the effect of climate on the timing of flowering of terrestrial plants at high latitudes is only moderately influenced by confounding effects, whereas the timing of phytoplankton blooms in high-latitude marine systems is highly dependent on ocean temperature and associated stratification and changes in nutrient availability.

Eastern boundary upwelling systems (Table 30-1, Figure 30-2). Recent research shows declining oxygen levels (*medium confidence*; Section 30.3.2.3) and deep penetration of warming in some regions. Regional estimates of CO_2 uptake are in line with global estimates, and ocean acidification has been detected with *high confidence* in most regions (Section 30.3.2.2; WGI AR5 Section 3.8.2).

The high latitude spring bloom systems of the NH show strong warming and associated effects (see above). In the North Pacific, the Bering Sea has undergone major changes in recent decades as a result of climate variability, climate change, and fishing impacts (Litzow et al., 2008; Mueter and Litzow, 2008; Jin et al., 2009; Hunt et al., 2010). Loss of sea ice has led to the retreat of the cold pool in parts of the Bering Sea, and northward expansion of productivity (Wang et al., 2006; Mueter and Lizow, 2008; Brown and Arrigo 2012; see also Section 30.5.1.1.2).

Marginal seas such as the East China Sea are also warming rapidly, with subsequent impacts such as declining primary productivity and fisheries yields as well as other ecological changes (Section 30.5.4.1). However, other human pressures including over-fishing, habitat alteration, and nutrient loading are important contributing factors and it is difficult to disentangle these from the impacts of climate change.

Semi-enclosed seas such as the Black and Baltic Seas and the Arabian/Persian Gulf show differing patterns of change over the past decades (Section 30.5.3.1). Expansions of hypoxic zones in the Baltic and Black Seas have been detected. Although there is *high confidence* that climate change has had a role, its magnitude is difficult to assess in light of other contributing factors. Coral reefs in the Arabian/Persian Gulf and Red Sea have experienced widespread bleaching in 1996 and 1998 associated with elevated temperature with *high confidence* that climate change has played a major role.

Warming of the Mediterranean has been associated with mass mortality events as well as invasions and spread of new warm water species,

resulting in the "tropicalization" of fauna with *high confidence* in a major role for climate change (Section 30.5.3.1.5). In many tropical regions and the subtropical gyres of the Pacific, Indian, and Atlantic, periodic heat stress related to climate change has combined with other local stresses to cause mass coral bleaching and mortality (see also Box CC-CR, Section 30.5).

In other regions, such as the California Current upwelling system, there is *very high confidence* in both the detection and attribution of ecological changes associated with climate change, but separating the effects of El Niño-Southern Oscillation (ENSO) and the PDO from those of anthropogenic climate change is not possible.

In overall terms, attributing observed local and regional changes in marine species and ecosystems to climate change remains an important question for ongoing research (Stock et al., 2010).

18.4. Detection and Attribution of Observed Climate Change Impacts in Human and Managed Systems

Observed impacts on human systems have received considerably less attention in previous IPCC reports and the scientific literature, compared to observed impacts on natural systems. Human systems' "normal state in the absence of climate change" is almost never stationary. Confounders other than climate change have been and continue to drive the normal evolution of these systems, with climate often playing a relatively minor role. Further, monitoring in many of the systems has been and continues to be inadequate. It is therefore difficult to detect and attribute the signal of climate change in the majority of human systems, food production systems constituting one noteworthy exception. There is emerging literature estimating the sensitivity to climate of many sectors within the human system (see Box 18-4), yet climate impacts are often not detectable over the impacts from non-climate confounders.

For some human systems, the clearest situations where a climate signal had a detectable and sometimes attributable impact are during extreme weather events. Impacts of extreme events and single event attribution are therefore discussed in Section 18.4.3, and the discussion is expanded to include responses to extreme weather for some sectors. Overall, the literature has made significant progress for certain sectors, such as food systems, since AR4. The following sections provide a synthesis of findings with regard to food systems, economic systems, human health, human security, and human livelihoods and poverty, which are documented in greater detail in Chapters 7, 9, 10, 11, 12, and 13. They also incorporate evidence from regional chapters and further available literature, especially for the discussion of extreme events, human security, and observed changes in indigenous communities.

18.4.1. Food Production Systems

Detection and attribution of climate change impacts in food systems is challenging, given that the behavior of the system in the absence of climate change is driven by a large number of other factors (Section 7.2.1). For cropping systems, these confounders include, but are not limited to, cultivar improvement and increased use of synthetic fertilizers, herbicides, and irrigation. These confounders are often not well measured in terms of their distribution across space and time. Further, it is difficult to quantify or model the exact relationship between these confounders and outcomes of interest (e.g., crop yield or pasture productivity). In addition, the role of farmers' behavior in response to climate change requires significant assumptions and has been shown to change over time (Section 7.2.1). The discussion below is limited to crop systems and fisheries, as literature is scarce on observed impacts for other important sources of food.

18.4.1.1. Agricultural Crops

A significant number of studies have provided impact estimates of observed changes in climate on cropping systems over the past few decades (e.g., Auffhammer et al., 2006; Kucharik and Serbin, 2008; Ludwig et al., 2009; Lobell et al., 2011; Tao et al., 2012; see also Figure 7-2). Over the past several decades, observed climate trends have adversely affected wheat and maize production for many regions, as well as the total global production of these crops (*medium confidence* in a minor role of climate change in overall production). Climate change impacts on rice and soybean yields over this time period have been small in major production regions and globally (*medium confidence*; Figure 7-2). In some high-latitude regions, such as the UK and northeast China, warming has benefitted crop production during recent decades (*high confidence* in a minor role of climate change; Section 7.2.1.1; Jaggard et al., 2007; Chen. C. et al., 2011). At the continental or global scale, observed trends in some climatic variables, including mean summer temperatures, attributed to anthropogenic activity (see Section 7.2.1.1; WGI AR5 Section 10.3.1 and Table 10-1) have had significant negative impacts on trends in yields for certain crops (Lobell and Field, 2007; You et al., 2009; Lobell et al., 2011).

Attributable trends have been found not only in the seasonal averages of climate variables, but also for extremes (WGI AR5 Section 10.6). Extreme rainfall events are widely recognized as important to cropping systems (Rosenzweig et al., 2002), and global scale changes in the patterns of rainfall extremes have been attributed to anthropogenic activity (Min et al., 2011). High nighttime temperatures are harmful to most crops, particularly for rice yield (Peng et al., 2004; Wassmann et al., 2009; Welch et al., 2010) and quality (Okada et al., 2009). Daytime extreme heat is also damaging and sometimes lethal to crops (Porter and Gawith, 1999; Schlenker and Roberts, 2009). At the global scale, trends in annual maximum daytime temperatures have been attributed to greenhouse gas emissions (Christidis et al., 2011; Zwiers et al., 2011), and similar observations have been made for the occurrence of very hot nights (WGI AR5 Section 10.6.1.1; Seneviratne et al., 2012).

Changing atmospheric conditions are affecting crops both positively and negatively. It is *virtually certain* that the increase in atmospheric CO_2 concentrations since preindustrial times has improved water use efficiency and yields most notably in C_3 crops. These effects are however of relatively minor importance when explaining total yield trends (Amthor, 2001; McGrath and Lobell, 2011). Emissions of CO_2 have been associated with tropospheric ozone (O_3) precursors (Morgan et al., 2006;

Box 18-4 | The Role of Sensitivity to Climate and Adaptation for Impact Models in Human Systems

Impacts of climate change on a measurable attribute of a human system occur only if (1) the attribute is sensitive to climate and (2) a change in climate has occurred. Many studies now attempt to quantify both climate sensitivity of various systems and observed changes in climate.

Assessment of the sensitivity of an outcome such as crop yields, heat-related mortality, or migration to climate relies on observed climate variability either across space (e.g., Schlenker et al., 2005), time (e.g., Mann and Emanuel, 2012), or space and time (e.g., Dell et al., 2012). Though there are many studies using climate variability across space, the lack of long observational weather time series required for exploring climate variability across space and time have limited the opportunities for study. A number of studies have instead estimated the sensitivity of outcomes to short-run fluctuations (e.g., weather) in order to project the future impacts of climate change (Deschênes and Greenstone, 2007, 2011), or attribute impacts for the past (Auffhammer et al., 2006). The issue with impact studies using a weather-based sensitivity measure is that they cannot provide estimates of impacts based on the sensitivity to climate. For example, farmers may respond to an unusually hot summer, which is a weather event, by applying more irrigation water. However, in the long run farmers may respond to a warmer climate by switching crops, changing irrigation technology, or abandoning farming altogether. The two sensitivities and resulting magnitudes of attributable impacts due to a change in weather versus a change in climate are therefore different. To detect and attribute a change in a system to climate change, one needs to combine a measure of sensitivity of the outcome to climate with climate observations under climate change.

Mills et al., 2007; see also Section 7.3.2.1.2). O_3 suppresses global output of major crops, with reductions estimated at roughly 10% for wheat and soy and 3 to 5% for maize and rice (Van Dingenen et al., 2009). Detected impacts are most significant for India and China, but can also be found for soybean and maize production in the USA in recent decades (Fishman et al., 2010).

18.4.1.2. Fisheries

Many new studies focus on the relationship between the dynamics of marine fish stocks and climate, suggesting a sensitivity to climate of these stocks and on the fisheries that exploit them (Hollowed et al., 2001; Roessig et al., 2004; Shriver et al., 2006; Brander, 2007). Some fisheries and aquaculture do not show evidence of climate change impacts (e.g., aquaculture in the UK and Ireland; Callaway et al., 2012), while many others do with both positive and negative changes (see also Sections 7.2.1.1, 18.3.4, 30.6.2.1).

There is *high confidence* in the detection of a climate change impact on the spatial distributions of marine fishes (Perry et al., 2005) and in the timing of events like spawning and migration (Sydeman and Bograd, 2009), with *high confidence* of a major role of climate change (see Sections 18.3.4, 30.4; Box CC-MB). This distributional shift is reflected in the species composition of harvest, with the relative share of warm water species increasing (Cheung et al., 2013). The impacts of ocean warming and acidification on fish stocks vary from region to region (Section 30.6.2.1). To date, the role of climate change in change in fish stocks and fishery yields is, in most cases, minor (*high confidence*) in relation to other factors such as harvesting, habitat modification, technological development, and pollution (Brander, 2010).

18.4.2. Economic Impacts, Key Economic Sectors, and Services

18.4.2.1. Economic Growth

In low-income countries, careful tracking of incomes and temperatures over an extended period, taking into account important confounders, shows that higher annual temperatures as well as higher temperatures averaged over 15-year periods result in substantially lower economic growth (Dell et al., 2012). This effect is not limited to the level of per capita income, but also to its rate of growth. Declining rainfall over the 20th century partly explains the slower growth of sub-Saharan economies relative to those of other developing regions (Barrios et al., 2006; Brown et al., 2011). Dell et al. (2009) find that 1°C of warming reduces income by 1.2% in the short run and by 0.5% in the long run. The difference is argued to be due to adaptation. Horowitz (2009) finds a much larger effect: a 3.8% drop in income in the long run for 1°C of warming. One proposed mechanism for this is the impact of heat stress on workers in the workplace (Dash and Kjellström, 2011; Dunne et al., 2013). Temperature shocks have negatively affected the growth of developing countries' exports, for which 1°C of warming in a given year reduced the growth rate of its exports by 2.0 to 5.7 percentage points (Jones and Olken, 2010). The export sectors most affected are agricultural and light manufacturing exports.

18.4.2.2. Energy Systems

Energy production and consumption is growing rapidly globally, with much of the growth taking place in low-income and emerging economies. Various parts of the energy sector are known to be sensitive

to climate change (cf. Ebinger and Vegara, 2011). Higher temperatures raise the demand for cooling and lower the demand for heating. Cooling demand is largest in the summer and in some areas peak loads during the summer months have increased, this peak being highly correlated with summer maximum temperatures (Franco and Sanstad, 2008). There are also opposing effects of warmer winters and summers on electricity and gas demand. Statistical studies have confirmed this U-shaped relationship of energy and electricity demand in temperature for the USA and elsewhere (Isaac and van Vuuren, 2009; Akpinar-Ferrand and Singh, 2010; Deschênes and Greenstone, 2011).

On the supply side, sensitivity to climatic factors such as ambient temperature, wind speeds, or snow and ice is well known for many energy technologies and part of the transmission infrastructure (see Sections 10.2.2-3); however, there are no studies available that discuss observed effects of climate change on the energy sector.

18.4.2.3. Tourism

Tourism is a climate sensitive economic sector and ample research has been performed to understand its sensitivity to climate change and impacts of (future) climate change on tourism, yet few studies have focused on detection and attribution of observed impacts (cf. Scott et al., 2008; see also Section 10.6).

A comparatively well-studied area is the sensitivity of the winter sports industry in lower lying areas to climate. For example, the increase in investment in artificial snow machines in the European Alps can be attributed with *high confidence* to a general decrease of snow depth, snow cover duration, and snowfall days since the end of the 1980s for low-elevation mountain stations (Durand et al., 2009; Valt and Cianfarra, 2010; Voigt et al., 2011), which in turn has been attributed to anomalous higher winter temperatures over the past 20 years (Marty, 2008).

Variability in precipitation, shrinking glaciers, and milder winters has been shown to negatively affect visitor numbers in winter sports areas in Europe and North America (Becken and Hay, 2007). Another indirect effect of climate change that has been reported is a rise in popularity of destinations that are perceived to be at risk from climate change (e.g., Eijgelaar et al. (2010) for Antarctic glaciers, or Farbotko (2010) for Tuvalu).

18.4.3. Impacts of Extreme Weather Events

The impacts of extreme weather events depend on the frequency and intensity of the events, as well as exposure and vulnerability of society and assets. The last several decades have seen changes in the frequency and intensity of extreme weather events including extreme temperature, droughts, heavy rainfall, and tropical and extratropical cyclones with *low* to *very high confidence*, depending on the type of extreme event (IPCC, 2012; WGI AR5 Chapter 2). However, the impacts of extreme weather events also depend on the vulnerability and exposure of systems. It is possible that climate change can affect vulnerability and exposure, but typically both are influenced primarily by non-climate confounders, most notably economic development.

18.4.3.1. Economic Losses Due to Extreme Weather Events

Extreme weather events can result in economic impacts related to damage to private and public assets as well as the temporary disruption of economic and social activities, long-term impacts, and impacts beyond the areas affected. Some economic and especially social impacts are not readily monetizable and are thus excluded from most economic assessments (Handmer et al., 2012, their Sections 4.5.1, 4.5.3).

Economic costs of extreme weather events have increased over the period 1960–2000 (*high confidence*), with insured losses increasing more rapidly than overall losses (Section 10.7.3; Handmer et al., 2012, their Sections 4.5.3.3, 4.5.4.1). This is also reflected by an increase in the frequency of extreme weather-related disasters over the same period (Neumayer and Barthel, 2011). Recent studies from Mexico and Colombia highlight both variability and positive trends in disaster frequency (unadjusted) losses and other damage metrics (Saldaña-Zorrilla and Sandberg, 2009; Marulanda et al., 2010; Rodriguez-Oreggia et al., 2013). However, the greatest contributor to increased cost is rising exposure associated with population growth and growing value of assets (*high confidence*; Bouwer et al., 2007; Bouwer, 2011; Barthel and Neumayer, 2012; Handmer et al., 2012, their Sections 4.2.2, 4.5.3.3, Box 4-2). To account for changes over time in the value of exposed assets, many studies attempt to normalize monetary losses by an overall measure of changes in asset value. A majority of studies have found no detectable trend in normalized losses (Bouwer, 2011). Studies on insured losses that in general meet higher data quality standards than data on overall losses due to thoroughly monitored payouts have focused on developed countries including Australia, Germany, Spain, the USA (Changnon, 2007, 2008, 2009a,b; Barredo et al., 2012; Barthel and Neumayer, 2012; Sander et al., 2013; see also Section 10.7.3). Studies of normalized losses from extreme winds associated with hurricanes in the USA (Miller et al., 2008; Pielke Jr. et al., 2008; Schmidt et al., 2010; Bouwer and Botzen, 2011) and the Caribbean (Pielke Jr. et al., 2003), tornadoes in the USA (Brooks and Doswell, 2002; Boruff et al., 2003; Simmons et al., 2013), and wind storms in Europe (Barredo, 2010) have failed to detect trends consistent with anthropogenic climate change, although some studies were able to find signals in loss records related to climate variability, such as damage and loss of life due to wildfires in Australia related to ENSO and Indian Ocean dipole phenomena (Crompton et al., 2010), or typhoon loss variability in the western North Pacific (Welker and Faust, 2013). Effects of adaptation measures (disaster risk prevention) on disaster loss changes over time cannot be excluded as research is currently not able to control for this factor (Neumayer and Barthel, 2011).

In conclusion, although there is *limited evidence* of a trend in the economic impacts of extreme weather events that is consistent with a change driven by observed climate change, climate change cannot be excluded as at least one of the drivers involved in changes of normalized losses over time in some regions and for some hazards.

18.4.3.2. Detection and Attribution of the Impacts of Single Extreme Weather Events to Climate Change

Although most studies on the relationship between climate change and extreme weather events have focused on changes over time in their

Table 18-3 | Illustrative selection of recent disasters related to extreme weather events, with description of the impact event, the associated climate hazard, recent climate trends relating to the weather event, and recent trends relating to the consequences of such a weather event.

Date and locale	Impact event	Associated climate hazard	Trends relating to likelihood of climate hazard	Trends relating to consequence of climate hazard
France, summer 2003	Approximately 15,000 excess deaths (Hémon and Jougla, 2003; Fouillet et al., 2006)	Record hot days/heat wave (Hémon and Jougla, 2003; Fouillet et al., 2006)	Increasingly frequent hot days and heat waves in recent decades (Perkins et al., 2012; Seneviratne et al., 2012) (*high confidence*)	• Aging population, increasing population, trends in marital status (Hémon and Jougla, 2003; Prioux, 2005; Fouillet et al., 2006; Rey et al., 2007) • Difficulties staffing health services, undeveloped early warning system (Lalande et al., 2003; Fouillet et al., 2008)
Atlantic and Gulf coasts of the United States, 2005	More than 1,000 deaths and more than US$100 billion in damage (Beven et al., 2008)	Record number of tropical storms, hurricanes, and category 5 hurricanes (Bell et al., 2006)	Recent increase in frequency but no clear century-scale trends in USA landfalling tropical storms or hurricanes (WGI AR5 Section 2.6.3, Knutson et al., 2010) (*high confidence*)	• More population, settlement, and wealth in coastal areas (Pielke Jr. et al., 2008; Schmidt et al., 2010) • Strengthening of building codes (IntraRisk, 2002)
Mozambique, early 2007	More than 100,000 people displaced by flooding (Foley, 2007; Artur and Hilhorst, 2012)	High rainfall in upper Zambezi Basin in preceding months; passage of Cyclone Favio (Thiaw et al., 2008)	Warming and decreasing rainfall leading to lower discharge of the Zambezi (Dai et al., 2009) (*low confidence*) Decreasing frequency of tropical cyclones in the Mozambique Channel during past 50 years (Mavume et al., 2009) (*medium confidence*)	• Increased settlement of Zambezi flood plain following dam construction (Foley, 2007) • Development of emergency response plans (Cosgrave et al., 2007; Foley, 2007)
Colombia, October–December 2010	Floods affecting 4 million people; US$7.8 billion total damage (Hoyos, N. et al., 2013)	Wettest year since records began 40 years ago (Martinez et al., 2011)	No clear trend in discharge of rivers in flood-affected areas since 1940 (Hoyos, N. et al., 2013) (*low confidence*)	• Rapid urbanization, with high concentration of residential areas in flood-prone areas (OSSO, 2013; Álvarez-Berríos et al., 2013) • Increasing vulnerability of rural population over the past decades and highly fragile urban systems (e.g., water and gas) (OSSO, 2013)
Pakistan, July–September 2010	Flooding leading to 2,000 deaths; 20 million affected; total loss US$10 billion (NDMA, 2011)	Exceptionally high monsoon rainfall over northern Pakistan during July and August (Houze Jr. et al., 2011; Rajeevan et al., 2011; Webster et al., 2011)	No substantial trend in heavy rainfall event frequency in northern Pakistan in past several decades (Wang, S.-Y. et al., 2011; Webster et al., 2011) (*low confidence*)	• Rapid population growth and expansion of formal and informal human settlements (Oxley, 2011) • Decreased risk through development of flood and disease warning systems and disaster planning (NDMA, 2011) • Increased risk from deforestation on mountainous slopes (Ali et al., 2006) • Recent unrest in north constrains ability of institutions to deliver basic services (World Bank and ADB, 2010)
European Russia, July–August 2010	Burned area >12,500 km (Müller, 2011)	Record hot days (Barriopedro et al., 2011; Müller, 2011) Unusually dry June–August (Bulygina et al., 2011)	Trends in temperature, precipitation, humidity, soil moisture, and snow cover toward less conducive climatic conditions for fire (Groisman et al., 2007) (*medium confidence*)	• Increased risk from draining of peat bogs in 1960s and earlier (Global Fire Monitoring Center, 2010; Müller, 2011) • Increased risk from poorly implemented devolution of forest management and forest fire protection in 2007 to regional administrations (Global Fire Monitoring Center, 2010)
Russia, summer 2010	Grain harvest 30% lower than forecast (Wegren, 2011)	Hottest June–August in at least 130 years, unusually dry June–August (Bulygina et al., 2011)	~1°C summer warming trend over last 70 years (Gruza and Mescherskaya, 2008; Bulygina et al., 2011) (*very high confidence*)	• Increase in grain production partially due to government support programs (Wegren, 2011)
Southeast Queensland, Australia, January 2011	Floods affecting >200,000 people; >30,000 homes flooded; damages and cost to economy of US$2.5–10 billion (Hayes and Goonetilleke, 2012)	2010 was the wettest year since 1974, with landfall of tropical cyclone in December and wet start to January resulting in highest flood since 1974 (Van den Honert and McAneney, 2011; Hayes and Goonetilleke, 2012).	Decreasing frequency of intense floods since 1840 (Van den Honert and McAneney, 2011) (*medium confidence*)	• Increased development in flood-prone urban areas (Van den Honert and McAneney, 2011) • Lack of development of riverine flood insurance (Van den Honert and McAneney, 2011; Ma et al., 2012)
Thailand, 2011	Prolonged inundation of urban and industrialized areas; manufacturing losses of about US$32 billion (World Bank, 2012)	One of the wettest monsoon seasons on record in middle and upper Chao Phraya Basin, resulting in flooding (Komori et al., 2012; Van Oldenborgh et al., 2012)	No detectable change in precipitation over the basin (Van Oldenborgh et al., 2012) (*low confidence*)	• Economic development focused on large industrial estates built in flood plains (Chongvilaivan, 2012; Courbage et al., 2012) • Recent spell of political instability (Courbage et al., 2012) • Subsidence from groundwater pumping (Phien-Wej et al., 2006)
Contiguous United States, summer 2012	Agricultural drought, with 57% of cropland and 43% of farms experiencing at least severe drought (Crutchfield, 2013)	Second warmest summer and warmest month (July) in the contiguous USA, and one of the driest March–July periods in the central USA in the 118-year record (Crouch et al., 2013; Kumar et al., 2013)	~0.5°C warming in summer over the last century (Menne et al., 2009) (*very high confidence*) No substantial long-term trend in drought occurrence (Peterson et al., 2013) (*medium confidence*)	Significant growth in area dedicated to soy and maize (FAOSTAT, 2013)

frequency and intensity, a few studies have focused on the contribution of climate change to specific events (WGI AR5 Section 10.6.2). Assessing the contribution of climate change to a specific event poses particular challenges, both in terms of methodology and communication of results (Allen, 2011; Curry, 2011; Hulme et al., 2011; Trenberth, 2011). Only a few studies have attempted to evaluate the role of climate change in the impacts of individual extreme weather events. For instance, Pall et al. (2011) and Kay et al. (2011), using observational constraints on climate and hydrologic model simulations, concluded that greenhouse gas emissions have increased the probability of occurrence of a comparable flooding event in autumn 2000 over the UK.

In highly temperature-sensitive regions, such as high mountains, several extreme impact events of recent decades can be qualitatively attributed to effects of long-term warming (*high confidence*), namely glacier lake outburst floods due to glacier recession and subsequent formation of unstable lakes (Evans and Clague, 1994; Carey, 2005; Bajracharya and Mool, 2009), debris flows from recently deglaciated areas, and rock fall and avalanches following the loss of mechanical support accompanying glacier retreat (Haeberli and Beniston, 1998; Oppikofer et al., 2008; Huggel et al., 2012b; Stoffel and Huggel, 2012; see also Section 18.3.1.3). Multi-step approaches can be used to evaluate the contributions of anthropogenic emissions to recent damaging extreme events (Hegerl et al., 2010).

Irrespective of whether a specific event can be attributed in part to climate change, there is ample evidence of the severity of related impacts on people and various assets. Both low- and high-income countries have been strongly impacted by extreme weather events in recent years, but the impacts relative to economic strength have been higher in low-income countries (Handmer et al., 2012). Similarly, at the national scale, poor or elderly people have been disproportionately affected, as documented for Hurricane Katrina in the USA in 2005 (Elliott and Pais, 2006; Bullard and Wright, 2010) or the 2003 European heat wave (Fouillet et al., 2008). Exacerbating effects of extreme weather events are mostly of non-climatic nature, including increasing exposure and urbanization, land use changes including deforestation, or vulnerable infrastructure. Table 18-3 lists a selection of recent weather-related disasters, and lists various factors contributing to long-term changes in the risk of damage, including recent climate change.

18.4.4. Human Health

IPCC AR4 (Confalonieri et al., 2007) concluded that there was *weak* to *moderate evidence* of effects of recent observed climate change on three main categories of health exposure (ranging from *low* to *medium confidence*): vectors of human infectious diseases (changes in distribution), allergenic pollen (changes in phenology), and extreme heat exposures (trend in increased frequency of very hot days and heat wave events). Overall, there was a lack of evidence for observed effects of climate change on human health outcomes, and this generally remains the case (see Chapter 11). Evaluation of the detection and attribution of impacts on health outcomes requires disentangling the roles of changes in exposures (e.g. patterns), control measures (e.g., vaccination, drug resistance), population structures (e.g., population aging), and reporting practices.

The most direct potential health impact of climate change is through exposure to higher temperatures, as the association between very hot days and increases in mortality is very robust (Section 11.4.1). Recent decades have seen a shift toward more frequent hot extremes and less frequent cold extremes (*high confidence*; Seneviratne et al., 2012; WGI AR5 Table 2.13). However, the translation of this trend in hazard to a trend in exposure is complicated by changes in social, environmental, and behavioral factors (e.g., Carson et al., 2006; see also Table 18-3) and interseasonal mortality relationships (Rocklöv et al., 2009; Ha et al., 2011). Climate change has contributed to a shift from cold-related mortality to heat-related mortality during recent decades in Australia (*medium confidence*; Bennett et al., 2013). In a similar shift in England and Wales, a contribution from anthropogenic climate change has been detected (*medium confidence*; Christidis et al., 2010).

For pollen production, changes in phenology have been consistently observed in mid- to high latitudes with, for example, earlier onset in Finland (e.g., Yli-Panula et al., 2009) and Spain (D'Amato et al., 2007; García-Mozo et al., 2010; see also Section 4.3) over the past few decades. In North America, the pollen season of ragweed (*Ambrosia* spp.) has been extended by 13 to 27 days since 1995 at latitudes above 44°N (Ziska et al., 2011). Allergic sensitization of humans has changed over a 25-year period in Italy, but the attribution to observed warming remains unclear (Ariano et al., 2010).

There is *limited evidence* regarding the role of observed warming in changes in tick-borne disease in mid- to high latitudes. While patterns of changes in tick-borne encephalitis (TBE) incidence in the Czech Republic match those expected from observed warming (Kriz et al., 2012), the upsurge of TBE in the 1980–1990s in Central and Eastern Europe generally has been attributed to socioeconomic factors (human behavior) rather than temperature (Šumilo et al., 2008, 2009). Changes in the latitudinal and altitudinal distribution of ticks in Europe and North America are consistent with observed warming trends (e.g., Gray et al., 2009; Ogden et al., 2010), but there is no evidence so far of any associated changes in the distribution of human cases of tick-borne diseases. There is *limited evidence* of a change in the distribution of rodent-borne infections in the USA (plague and tularemia) consistent with observed warming (Nakazawa et al., 2007). Specifically, a northward shift of the southern edge of the distributions of the diseases (based on human case data for period 1965–2003) was observed. There was no change detected in the northern edge of the distributions, however.

Globally, the dominant trend concerning malaria has been a contraction of the geographical range and a decrease in endemicity over the past century due to changes in land cover, behavior, and health care (Gething et al., 2010). Given that the mosquito vector is climate sensitive, however, there may be specific locations where climate change matches the influence of these other factors. In the Kericho region of Kenya, both increasing incidence and warming have been observed over several decades (Omumbo et al., 2011). Modelling suggests that the gradual warming is inducing an amplified nonlinear response in malaria incidence (Alonso et al., 2011). A detailed review concluded that decadal temperature changes have played at least a minor role in these malaria trends in the East African highlands (*low confidence*; Chaves and Koenraadt, 2010).

Box 18-5 | Detection, Attribution, and Traditional Ecological Knowledge

Indigenous and local peoples often possess detailed knowledge of climate change that is derived from observations of environmental conditions over many generations. Consequently, there is increasing interest in merging this traditional ecological knowledge (TEK)—also referred to as indigenous knowledge—with the natural and social sciences in order to better understand and detect climate change impacts (Huntington et al., 2004; Parry et al., 2007; Salick and Ross, 2009; Green and Raygorodetsky, 2010; Ford et al., 2011; Diemberger et al., 2012). TEK, however, does not simply augment the sciences, but rather stands on its own as a valued knowledge system that can, together with or independently of the natural sciences, produce useful knowledge for climate change detection or adaptation (Agrawal, 1995; Cruikshank, 2001; Hulme, 2008; Berkes, 2009; Byg and Salick, 2009; Maclean and Cullen, 2009; Wohling, 2009; Ziervogel and Opere, 2010; Ford et al., 2011; Herman-Mercer et al., 2011).

Cases in which TEK and scientific studies both detect the same phenomenon offer a higher level of confidence about climate change impacts and environmental change (Huntington et al., 2004; Laidler, 2006; Krupnik and Ray, 2007; Salick and Ross, 2009; Gamble et al., 2010; Green and Raygorodetsky, 2010; Alexander et al., 2011; Cullen-Unsworth et al., 2012). Evidence is available in particular from Nordic and Mountain peoples, for example, from Peru's Cordillera Blanca mountains (Bury et al., 2010; Carey, 2010; Baraer et al., 2012; Carey et al., 2012b), Tibet (Byg and Salick, 2009), and Canada (Nichols et al., 2004; Laidler, 2006; Krupnik and Ray, 2007; Ford et al., 2009; Aporta et al., 2011). TEK can also inspire scientists to study new issues in the detection of climate change impacts. In one case, experienced Inuit weather forecasters in Baker Lake, Nunavut, Canada, reported that it had become increasingly difficult for them to predict weather, suggesting an increase of weather variability and anomalies in recent years. To test Inuit observations, scientists analyzing hourly temperature data over a 50-year period confirmed that afternoon temperatures fluctuated much more during springtime during the last 20 years—precisely when Inuit forecasters noted unpredictability—than they had during the previous 30 years (Weatherhead et al., 2010).

Despite frequent confluence between TEK and scientific observations, there are sometimes discrepancies between them, indicating uncertainty in the identification of climate change impacts. They can arise because TEK and scientific studies frequently focus on different and distinct scales that make comparison difficult. Local knowledge may fail to detect regional environmental changes while scientific regional or global scale analyses may miss local variation (Wohling, 2009; Gamble et al., 2010). Furthermore, TEK-based observations and related interpretations necessarily need to be viewed within the context of the respective cultural, social, and political backgrounds (Agrawal, 1995). Therefore, a direct translation of TEK into a natural science perspective is often not feasible.

18.4.5. Human Security

A small number of studies have examined the connection between the collapse of civilizations and large-scale climate disruptions such as severe or prolonged drought. However, both the detection of a climate change effect and an assessment of the importance of its role can be made only with *low confidence* owing to limitations on both historical understanding and data. Some studies have suggested that levels of warfare in Europe and Asia were relatively high during the Little Ice Age (Parker, 2008; Brook, 2010; Tol and Wagner, 2010; White, 2011; Zhang et al., 2011), but for the same reasons the detection of the effect of climate change and an assessment of its importance can be made only with *low confidence*. There is no evidence of a climate change effect on interstate conflict in the post-World War II period.

Most recent research in this area has focused on the relationship between interannual climate variability in temperature, precipitation, and other climate variables and civil conflict, with most studies focusing on Africa (Hsiang et al., 2013; see also Section 12.5). A number of studies have identified statistical relationships (Miguel et al., 2004; Hendrix and Glaser, 2007; Hsiang et al., 2011), but the results have been challenged (Buhaug et al., 2010; Theisen et al., 2011; Buhaug and Theisen, 2012; Slettebak, 2012) on both technical and substantive grounds. The issue is further complicated by the focus on interannual variability—rather than climate change—and civil conflict. Though a plausible argument could be made that climate change has increased interannual variability and has, therefore, contributed positively to the rate of civil conflict, this argument has not been tested in the literature. For these reasons, neither the detection of an effect of climate change on civil conflict nor an assessment of the magnitude of such an effect can currently be made with a degree of confidence.

Several studies have examined links between climate variability and small-scale communal violence (Adano et al., 2012; Butler and Gates, 2012; Hendrix and Salehyan, 2012; Raleigh and Kniveton, 2012; Theisen, 2012). As with larger-scale civil conflict, this work has focused on climate

Table 18-4 | Cases of regional livelihood impacts associated with weather- and climate-related events, inter-annual climate variability, or climate change (see also Table 18-3; Section 13.2.1.1).

Impacted population	Climate-related driver	Impact on livelihood	Reference
Small-scale farmers, Ghana	Drought (past 20–30 years)	Landscape transformation causing emotional distress, sense of loss of belonging	Tschakert et al. (2013)
Middle-class farmers, Australia	Drought (2000s)	Landscape transformation, income loss from agriculture, social conflict, poverty	Alston (2011)
Arctic indigenous peoples	Warming (past decades)	Changing ice and snow conditions, dwindling access to hunting grounds	Section 28.2.4; Table 18-9; Hovelsrud et al. (2008); Ford (2009a); Brubaker et al. (2011); Arctic Council (2013); Crate (2013)
Urban populations in Maputo, Accra, Nairobi, Lagos, Kampala	Flood frequency and severity increase (1990s and 2000s)	Direct impacts on people and loss of physical assets (e.g., housing)	Douglas et al. (2008); Adelekan (2010)
Industry workers in India	Temperature variability and heat waves (1960s to present)	Decrease of fully workable days since 1960; limited ability to carry out physical work; health impacts	Ayyappan et al. (2009); Balakrishnan et al. (2010); Dash and Kjellström (2011)
Farmers in Subarnabad, Bangladesh	Sea level rise (~1980s to present)	Salt water intrusion; shift from agriculture to shrimp farming; loss of agricultural livelihoods	Pouliotte et al. (2009)
Women farmers, Ghana	Rainfall-related climate variability (~1990s and 2000s)	Adaptation practices in agriculture produce gender inequalities.	Carr (2008)
Cambodian rice farmers	Warming, rainfall-related climate variability (1980s to present)	Shift in income generation patterns between men and women	Resurreccion (2011)
Poor children in Africa and Latin America	Weather- and climate-related events (1980s to present)	Food price shocks, reduced caloric intake, physical stunting, long-term effects such as reduced lifetime earnings	Alderman (2010)
Smallholder farmers in highlands of Bolivia	Locally perceived changes in temperature means and extremes, and rainfall seasonality (~1990s and 2000s)	Stress on household resources due to need to respond to increasing plant pests; switching to other crop types or livestock	McDowell and Hess (2012)

variability rather than on climate change, so neither the detection of the effect of climate change nor an assessment of its magnitude can currently made with a degree of confidence.

Finally, efforts have been made to establish a link between high temperatures and violent crime (Anderson, 1987; Field, 1992; Anderson, 2001; Rotton and Cohn, 2001; Butke and Sheridan, 2010; Breetzke and Cohn, 2012; Gamble and Hess, 2012). However, the findings remain controversial with other studies identifying non-climate factors as explaining variations in the rate of violent crime (Kawachi et al., 1999; Fajnzylber et al., 2002; Neumayer, 2003; Cole and Gramajo, 2009). Again, the focus in this work has been on weather rather than climate and, in light of this and the equivocal nature of the results, neither the detection of a climate change effect nor an assessment of its magnitude can currently be made with a degree of confidence.

The impact of future climate change on human displacement and migration has been identified as an emerging risk (Section 19.4.2.1). The social, economic, and environmental factors underlying migration are complex and varied (see, e.g., Black et al., 2011) and it has not been possible to detect the effect of observed climate change nor assess its magnitude with any degree of confidence (see also Section 12.4.1.1). Migration in response to climate-related events has been identified in sub-Saharan Africa (Marchiori et al., 2012), with evidence from North America a subject of disagreement (Auffhammer and Vincent, 2012; Feng et al., 2012; Feng and Oppenheimer, 2012).

18.4.6. Livelihoods and Poverty

The vulnerability of the world's poor to climate change, and more generally the sensitivity of many livelihood aspects to climate variability, has been shown in this and earlier IPCC reports (see Chapter 13). However, available research about climate-related effects on livelihood and poverty has focused on impacts of climate extremes or year to year climate variability rather than long-term climatic trends, resulting in a paucity of evidence on observed impacts of climate change on livelihoods and poverty. Moreover, detection of changes in livelihood aspects is often difficult due to a lack of observations (Section 13.2.1), while multiple confounding factors and lack of both adequate climate data and system understanding preclude attribution (Nielsen and Reenberg, 2010).

Table 18-4 summarizes examples of impacts on livelihoods related to climatic trends, climate variability, and extreme weather events. Impacted natural assets include land, water, fish stocks, and livestock (Osbahr et al., 2008; Bunce et al., 2010). There is growing concern about negative effects of climate change and ocean acidification on marine and coastal fisheries, and the livelihoods of fisherfolks (Cooley and Doney, 2009; Badjeck et al., 2010); however, there are no studies evaluating observed impacts.

Climate-related impacts disproportionately affect poor populations, thus increasing social and economic inequalities, both in urban and rural areas, and in low-, middle-, and high-income countries (Sections 13.1.4, 13.2.1). Evidence for poor people in high-income nations being disproportionately affected by extreme weather events comes, for instance, from 2005 U.S. Hurricane Katrina (Elliott and Pais, 2006; Bullard and Wright, 2010; see also Section 13.2.1.5) or severe drought in Australia (Alston, 2011). Glacial lake outburst floods in the Peruvian Andes also affected different populations depending on their degree of exposure, level of vulnerability, race, ethnicity, and socioeconomic class (Carey, 2010; Carey et al., 2012b). Owing to gender-specific roles within the household, communities, and wider sociopolitical and institutional networks, a gender bias has been found in observations of impacts of extreme weather events and climate variability (Carr, 2008; Arora-Jonsson, 2011; Nightingale, 2011; see also Box 13-1).

Poor people living in hazard exposed areas in Africa and Latin America were increasingly affected by floods and landslides in the 1990s and 2000s (*high confidence*; Handmer et al., 2012); however, most of this trend was due to increased urbanization in such areas (Douglas et al., 2008; Hardoy and Pandiella, 2009). There is evidence of a decline in average precipitation in West Africa since 1960 (Lacombe et al., 2012), including repeated droughts (Dietz et al., 2004; Armah et al., 2011), which in some cases has been partly attributed to anthropogenic climate forcing (Held et al., 2005; Jenkins et al., 2005; Biasutti and Giannini, 2006). However, there is only *limited evidence* of changes in poverty among affected small-holder and subsistence farmers that can be attributed to climate drivers such as rainfall decline and droughts (Section 13.2.1).

Livelihoods of indigenous people in the Arctic have been identified as among the most severely affected by climate change, including food security aspects, traditional travel and hunting, and cultural values and references (Hovelsrud et al., 2008; Ford et al., 2009; Ford, 2009a,b; Beaumier and Ford, 2010; Pearce et al., 2010; Olsen et al., 2011; Eira, 2012; Crate, 2013; see also Box 18-5, Table 18-9). Impacts of rising temperatures, increased variability, and weather extremes on crops and livestock of indigenous people in highlands were reported from Tibet Autonomous Region, China (Byg and Salick, 2009), and the Andes of Bolivia (McDowell and Hess, 2012).

18.5. Detection and Attribution of Observed Climate Impacts across Regions

Since the AR4, significant new knowledge about detected impacts of recent climate change has been gained from all continents and oceans

Table 18-5 | Observed impacts of climate change reported since AR4 on mountains, snow, and ice, over the past several decades, across major world regions, with descriptors for (1) the confidence in detection of a climate change impact; (2) the relative contribution of climate change to the observed change, compared to that of non-climatic drivers; (3) the main climatic driver(s) causing the impacts; (4) the reference behavior of the system in the absence of climate change; and (5) the confidence in attribution of the impacts to climate change. References to related chapters in this report are given as well as key references to other IPCC reports and the scientific literature. Absence of climate change impacts from this table does not imply that such impacts have not occurred.

	Mountains, snow and ice	References	Confidence in detection	Role of climate	Climate driver	Reference behavior	Confidence in attribution
Africa	Retreat of tropical highland glaciers in East Africa	Mölg et al. (2008, 2012); Taylor et al. (2009)	*Very high*	Major	Warming, drying	No change	*High*
Europe	Retreat of Alpine, Scandinavian, and Icelandic glaciers	WGI AR5 Section 4.3.3; Bauder et al. (2007); Björnsson and Pálsson (2008); Paul and Haeberli (2008); WGMS (2008); Zemp et al. (2009); Andreassen et al. (2012); Marzeion et al. (2012); Gardner et al. (2013)	*Very high*	Major	Warming	No change	*High*
	Increase in rock slope failures in western Alps	Sections 18.3.1.3 and 23.3.1.4; Fischer et al. (2012); Huggel et al. (2012a)	*High*	Major	Warming	No change	*Medium*
Asia	Permafrost degradation in Siberia, Central Asia, and the Tibetan Plateau	WGI AR5 Section 4.7.2; Section 24.4.2.2; Romanovsky et al. (2010); Yang et al. (2013)	*High*	Major	Warming	No change	*High*
	Shrinking mountain glaciers across most of Asia	WGI AR5 Section 4.3.3; Section 24.4.1.2; Box 3-1; Bolch et al. (2012); Cogley (2012); Gardelle et al. (2012); Kääb et al. (2012); Yao et al. (2012); Gardner et al. (2013); Stokes et al. (2013)	*High*	Major	Warming	No change	*Medium*
Australasia	Substantial reduction in ice and glacier ice volume in New Zealand	WGI AR5 Section 4.3.3; Table 25-1; Chinn et al. (2012)	*High*	Major	Warming	No change	*Medium*
	Significant decline in late-season snow depth at three out of four alpine sites in Australia 1957–2002	Table 25-1; Nicholls (2006); Hennessy et al. (2008)	*High*	Major	Warming	No change	*Medium*
North America	Shrinkage of glaciers across western and northern North America	WGI AR5 Section 4.3.3; Gardner et al. (2013)	*High*	Major	Warming	No change	*High*
	Decreasing amount of water in spring snowpack in western North America 1960–2002	Stewart et al. (2005); Mote (2006); Barnett et al. (2008)	*High*	Major	Warming	No change	*High*
South and Central America	Shrinkage of Andean glaciers	WGI AR5 Section 4.3.3; Section 27.3.1.1; Table 27-3; Vuille et al. (2008); Bradley et al. (2009); Jomelli et al. (2009); Poveda and Pineda (2009); Marzeion et al. (2012); Gardner et al. (2013); Rabatel et al. (2013)	*High*	Major	Warming	No change	*High*
Polar regions	Decreasing Arctic sea ice cover in summer	WGI AR5 Section 4.2.2.1; ACIA (2005); AMAP (2011)	*Very high*	Major	Air and ocean warming, change in ocean circulation	No change	*High*
	Reduction in ice volume in Arctic glaciers	WGI AR5 Section 4.3.3; ACIA (2005); Nuth et al. (2010); AMAP (2011); Gardner et al. (2011, 2013); Moholdt et al. (2012)	*Very high*	Major	Warming	No change	*High*
	Decreasing snow cover across the Arctic	Section 28.2.3.1; AMAP (2011); Callaghan et al. (2011)	*High*	Major	Warming	No change	*Medium*
	Widespread permafrost degradation, especially in the southern Arctic	Section 28.2.1.1; AMAP (2011); Olsen et al. (2011)	*High*	Major	Warming	No change	*High*
	Ice mass loss along coastal Antarctica	WGI AR5 Sections 4.3.3, 4.4, and 10.5.2.1; Gardner et al. (2013); Miles et al. (2013)	*Medium*	Major	Warming	No change	*Medium*

Table 18-6 | Observed impacts of climate change reported since AR4 on rivers, lakes, and soil moisture, over the past several decades, across major world regions, with descriptors for (1) the confidence in detection of a climate change impact; (2) the relative contribution of climate change to the observed change, compared to that of non-climatic drivers; (3) the main climatic driver(s) causing the impacts; (4) the reference behavior of the system in the absence of climate change; and (5) the confidence in attribution of the impacts to climate change. References to related chapters in this report are given as well as key references to other IPCC reports and the scientific literature. Absence of climate change impacts from this table does not imply that such impacts have not occurred.

	Rivers, lakes, and soil moisture	References	Confidence in detection	Role of climate	Climate driver	Reference behavior	Confidence in attribution
Africa	Reduced discharge in West African rivers	d'Orgeval and Polcher (2008); Dai et al. (2009); Di Baldassarre et al. (2010)	*Medium*	Major	Reduced precipitation	No change	*Low*
	Lake surface warming and water column stratification increases in the Great Lakes and Lake Kariba	Section 22.3.2.2; Tierney et al. (2010); Ndebele-Murisa et al. (2011); Powers et al. (2011)	*High*	Major	Warming	No change	*High*
	Increased soil moisture drought in the Sahel since 1970, partially wetter conditions since 1990	Section 22.2.2.1; Hoerling et al. (2006); Giannini et al. (2008); Greene et al. (2009); Seneviratne et al. (2012)	*Medium*	Major	Change in precipitation	No change	*Medium*
Europe	Changes in the occurrence of extreme river discharges and floods	Section 23.2.3; Schmocker-Fackel and Naef (2010); Beniston et al. (2011); Cutter et al. (2012); Vorogushyn and Merz (2012); Kundzewicz et al. (2013)	*Low*	Minor	Change in precipitation; change in extreme precipitation	No change	*Very low*
Asia	Changes in water availability in many Chinese rivers	Table SM24-4; Zhang et al. (2007); Zhang, S. et al. (2008)	*High*	Minor	Change in precipitation	Changes due to land use	*Low*
	Increased flow in several rivers in China due to shrinking glaciers	Casassa et al. (2009); Li et al. (2010); Zhang, Y. et al. (2008)	*High*	Major	Warming	No change	*High*
	Earlier timing of maximum spring flood in Russian rivers	Section 28.2.1.1; Shiklomanov et al. (2007); Tan et al. (2011)	*High*	Major	Warming	No change	*Medium*
	Reduced soil moisture in North Central and Northeast China 1950–2006	Sections 24.3.1 and 24.4.1.2; Sheffield and Wood (2007); Wang, A. et al. (2011); Seneviratne et al. (2012)	*Medium*	Major	Warming; change in precipitation	No change	*Medium*
	Surface water degradation in parts of Asia	Section 24.4.1.2; Prathumratana et al. (2008); Delpla et al. (2009); Huang et al. (2009)	*Medium*	Minor	Warming; change in precipitation	Changes due to land use	*Medium*
Australasia	Intensification of hydrological drought due to regional warming in Southeast Australia	Table 25-1; Nicholls (2006); Cai et al. (2009)	*Low*	Minor	Warming	No change	*Low*
	Reduced inflow in river systems in southwestern Australia (since the mid-1970s)	Table 25-1; Section 25.5.1; Cai and Cowan (2006); Nicholls (2010)	*High*	Major	Change in precipitation; warming	No change	*High*
North America	Shift to earlier peak flow in snow dominated rivers in western North America	Barnett et al. (2008)	*High*	Major	Warming; change in snow	No change	*High*
	Runoff increases in the midwestern and northeastern USA	Georgakakos et al. (2013)	*High*	Minor	Change in precipitation; warming	No change	*Medium*
South and Central America	Changes in extreme flows in Amazon River	Section 27.3.1.1; Butt et al. (2011); Wang, G. et al. (2011); Espinoza et al. (2013)	*High*	Major	Change in precipitation; change in extreme precipitation	No change	*Medium*
	Changing discharge patterns in rivers in the Western Andes; for major river basins in Colombia discharge has decreased during the last 30–40 years	Section 27.3.1.1; Table 27-3; Vuille et al. (2008); Casassa et al. (2009); Poveda and Pineda (2009); Baraer et al. (2012); Rabatel et al. (2013)	*Medium*	Major	Warming	No change	*Medium*
	Increased streamflow in sub-basins of the La Plata River	Section 27.3.1.1; Pasquini and Depetris (2007); Krepper et al. (2008); Saurral et al. (2008); Conway and Mahé (2009); Krepper and Zucarelli (2010); Doyle and Barros (2011)	*High*	Major	Change in precipitation	Increase due to land use	*High*
Polar regions	Increased river discharge for large circumpolar rivers (1997–2007)	Section 28.2.1.1; Overeem and Syvitsky, (2010)	*High*	Major	Warming; change in precipitation; change in snow cover	No change	*Low*
	Winter minimum river flow increase in most sectors of the Arctic	Section 28.2.1.1; Tan et al. (2011)	*High*	Major	Warming; change in snow cover	No change	*Medium*
	Increasing lake water temperatures 1985–2009, prolonged ice-free seasons	Section 28.2.1.1; Callaghan et al. (2010); Schneider and Hook (2010)	*Medium*	Major	Warming	No change	*Medium*
	Thermokarst lakes disappear due to permafrost degradation in the low Arctic, new ones created in areas of formerly frozen peat	Section 28.2.1.1; Riordan et al. (2006); Marsh et al. (2008); Prowse and Brown (2010)	*High*	Major	Warming	No change	*High*
Small islands	Increased water scarcity in Jamaica	Gamble et al. (2010); Jury and Winter (2010)	*Low*	Minor	Change in precipitation	Increase due to water use	*Very low*

Table 18-7 | Observed impacts of climate change reported since AR4 on terrestrial ecosystems, over the past several decades, across major world regions, with descriptors for: (1) the confidence in detection of a climate change impact; (2) the relative contribution of climate change to the observed change, compared to that of non-climatic drivers; (3) the main climatic driver(s) causing the impacts; (4) the reference behavior of the system in the absence of climate change; and (5) the confidence in attribution of the impacts to climate change. References to related chapters in this report are given as well as key references to other IPCC reports and the scientific literature. Absence of climate change impacts from this table does not imply that such impacts have not occurred.

	Terrestrial ecosystems	References	Confidence in detection	Role of climate	Climate driver	Reference behavior	Confidence in attribution
Africa	Tree density decreases in Western Sahel and semi-arid Morocco	Section 22.3.2.1; Gonzalez et al. (2012); Le Polain de Waroux and Lambin (2012)	*Medium*	Major	Change in precipitation	Changes due to land use	*Medium*
	Range shifts of several southern plants and animals: South African bird species polewards; Madagascan reptiles and amphibians upwards; Namib aloe contracting ranges	Table 22-3; Foden et al. (2007); Raxworthy et al. (2008); Hockey and Midgley (2009); Hockey et al. (2011)	*High*	Major	Warming	Changes due to land use	*Medium*
	Wildfires increase on Mt. Kilimanjaro	Table 22-3; Hemp (2005)	*Medium*	Major	Warming; drying	No change	*Low*
Europe	Earlier greening, earlier leaf emergence and fruiting in temperate and boreal trees	Section 4.3.2.1; Menzel et al. (2006)	*High*	Major	Warming	No change	*High*
	Increased colonization of alien plant species in Europe	Section 4.2.4.6; Table 23-6; Walther et al. (2009)	*Medium*	Major	Warming	Some invasion	*Medium*
	Earlier arrival of migratory birds in Europe since 1970	Section 4.2.4.6; Table 23-6; Møller et al. (2008)	*Medium*	Major	Warming	No change	*Medium*
	Upward shift in tree line in Europe	Section 18.3.2.3; Table 23-6; Gehrig-Fasel et al. (2007); Lenoir et al. (2008)	*Medium*	Major	Warming	Changes due to land use	*Low*
	Increasing burnt forest areas during recent decades in Portugal and Greece	Table 23-6; Camia and Amatulli (2009); Hoinka et al. (2009); Costa et al. (2011); Koutsias et al. (2012)	*High*	Major	Warming; change in precipitation	Some increase due to land use	*High*
Asia	Changes in plant phenology and growth in many parts of Asia (earlier greening), particularly in the north and the east	Sections 4.3.2.1 and 24.4.2.2; Figure 4-4; Ma and Zhou (2012); Panday and Ghimire (2012); Shrestha et al. (2012); Ogawa-Onishi and Berry (2013)	*High*	Major	Warming	No change	*Medium*
	Distribution shifts in many plant and animal species, particularly in the north of Asia, upwards in elevation or polewards	Sections 4.3.2.5 and 24.4.2.2; Figure 4-4; Moiseev et al. (2010); Chen et al. (2011); Jump et al. (2012); Ogawa-Onishi and Berry (2013)	*High*	Major	Warming	No change	*Medium*
	Invasion of Siberian larch forests by pine and spruce during recent decades	Section 24.4.2.2; Kharuk et al. (2010); Lloyd et al. (2011)	*Medium*	Major	Warming	No change	*Low*
	Advance of shrubs into the Siberian tundra	Sections 4.3.3.4, 24.4.2.2, and 28.2.3.1; Henry and Elmendorf (2010); Blok et al. (2011)	*High*	Major	Warming	No change	*High*
Australasia	Changes in genetics, growth, distribution, and phenology of many species, in particular birds, butterflies and plants in Australia	Table 25-3; Chambers (2008); Chessman (2009); Green (2010); Kearney et al. (2010); Keatley and Hudson (2012); Chambers et al. (2013b)	*High*	Major	Warming	Fluctuations due to variable local climates, land use, pollution, invasive species	*High*
	Expansion of some wetlands and contraction of adjacent woodlands in southeast Australia	Table 25-3; Keith et al. (2010)	*Medium*	Major	Change in precipitation; warming	No change	*Low*
	Expansion of monsoon rainforest at expense of savannah and grasslands in north Australia	Table 25-3; Banfai and Bowman (2007); Bowman et al. (2010)	*Medium*	Major	Change in precipitation; increased CO_2	No change	*Medium*
	Migration of glass eels advanced by several weeks in Waikato River, New Zealand	Table 25-3; Jellyman et al. (2009)	*Medium*	Major	Warming	No change	*Low*

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of the world, as assessed in Chapters 22 to 30 of this report. Tables 18-5 to 18-9 summarize impacts in major natural and human systems, at the local to continental scale, for which assessment of the role of climate as one driver has been possible. The following paragraphs provide a summary of recent climate changes in these regions along with notes about particular challenges in the regional assessments.

For much of *Africa*, knowledge about recent climate change is limited, owing to weak climate monitoring and gaps in coverage that continue to exist. On the other hand, the low natural temperature variability over the continent allows earlier detection of warming signals. Thus there is *medium* to *high confidence* in regional warming, with *low* to *high confidence* in attribution to anthropogenic emissions. A main regional feature has been the drying of the Sahel during the decades following 1970, but that trend has halted during the most recent decade (Hoerling et al., 2006; Giannini et al., 2008; Greene et al., 2009; Seneviratne et al., 2012). African natural and human systems present challenges for the potential detection and attribution of responses to climate change. Given the weak spatial and temporal variations in temperature, there is smaller scope for migrational and phenological

Table 18-7 (continued)

	Terrestrial ecosystems	References	Confidence in detection	Role of climate	Climate driver	Reference behavior	Confidence in attribution
North America	Phenology changes and species distribution shifts upward in elevation and northward across multiple taxa	Section 26.4.1; Parmesan and Galbraith (2004); Parmesan (2006); Kelly and Goulden (2008); Moritz et al. (2008); Tingley et al. (2009)	*High*	Major	Warming	No change	*Medium*
	Increased wildfire frequency in subarctic conifer forests and tundra	Section 28.2.3.1; Mack et al. (2011); Mann et al. (2012)	*High*	Major	Warming	No change	*Medium*
	Regional increases in tree mortality and insect infestations in forests	Section 26.4.2.1; Van Mantgem et al. (2009); Peng et al. (2011)	*Medium*	Minor	Warming	No change	*Low*
	Increase in wildfire activity, fire frequency and duration, and burnt area in forests of the western US and boreal forests in Canada	Box 26-2; Gillett et al. (2004); Westerling et al. (2006); Girardin et al. (2013)	*High*	Minor	Warming; change in precipitation	Changes due to land use and fire management	*Medium*
South and Central America	Increased tree mortality and forest fire in the Amazon	Section 4.3.3.1.3; Phillips et al. (2009)	*Medium*	Minor	Warming	No change	*Low*
	Degrading and receding rainforest in the Amazon	Sections 18.3.2.4, 27.2.2.1, and 27.3.2.1; Etter et al. (2006); Nepstad et al. (2006); Oliveira et al. (2007); Wassenaar et al. (2007); Killeen et al. (2008); Nepstad and Stickler (2008)	*Low*	Minor	Warming	Deforestation and land degradation	*Low*
Polar regions	Increase in shrub cover in tundra in North America and Eurasia	Section 28.2.3.1.2; Tape et al. (2006); Walker et al. (2006); Henry and Elmendorf (2010); Blok et al. (2011); Elmendorf et al. (2012); Tape et al. (2012)	*High*	Major	Warming	No change	*High*
	Advance of Arctic tree-line in latitude and altitude	Section 28.2.3.1.2; AMAP (2011); Hedenås et al. (2011); Van Bogaert et al. (2011)	*High*	Major	Warming	No change	*Medium*
	Loss of snow-bed ecosystems and tussock tundra	Section 28.2.3.1.2; Björk and Molau (2007); Molau (2010a); Hedenås et al. (2011); Callaghan et al. (2013)	*High*	Major	Warming; change in precipitation	No change	*High*
	Impacts on tundra animals from increased ice layers in snow pack, following rain-on-snow events	Section 28.2.3.1.3; Callaghan et al. (2011); Hansen et al. (2013)	*Medium*	Major	Change in precipitation; warming	No change	*Medium*
	Changes in breeding area and population size of subarctic birds, due to snowbed reduction and/or tundra shrub encroachment	Molau (2010b); Callaghan et al. (2013)	*High*	Major	Warming	No change	*Medium*
	Increase in plant species ranges in the West Antarctic Peninsula and nearby islands over the past 50 years	Section 28.2.3.2; Fowbert and Smith (1994); Parnikoza et al. (2009)	*High*	Major	Warming	No change	*High*
	Increasing phytoplankton productivity in Signy Island lake waters	Quayle et al. (2002); Laybourn-Parry (2003)	*High*	Major	Warming	No change	*High*
Small islands	Changes in tropical bird populations in Mauritius	Section 29.3.2; Senapathi et al. (2011)	*Medium*	Major	Change in precipitation	No change	*Medium*
	Decline of an endemic plant in Hawai'i	Krushelnycky et al. (2013)	*Medium*	Major	Warming; change in precipitation	No change	*Medium*
	Upward trend in tree lines and associated fauna on high-elevation islands	Section 29.3.2; Benning et al. (2002); Jump et al. (2006)	*Low*	Minor	Warming	No change	*Low*

responses to anthropogenic climate change than in other parts of the world. High-quality monitoring is relatively sparse in time and space, and is often unsuitable for detecting changes across margins and borders where responses to climate change are most expected. The dearth of studies examining attribution questions means it is currently difficult to estimate the degree to which studies are selectively published based on results, and thus to determine whether each attribution study is indicative only of local reasons for concern or if it is more generally representative of a broader domain.

Amongst all continents, *Europe* has the longest tradition in climate monitoring. Warming has been occurring across the continent in all seasons, with an associated decreasing frequency of cold extremes and increasing frequency of hot extremes (Seneviratne et al., 2012). The Mediterranean basin has been getting drier, while northern areas have been getting wetter (Section 23.2.2.1), with a general increase in the frequency of extreme wet events everywhere (Seneviratne et al., 2012).

Asia spans a particularly wide range of climate types. Warming has been observed throughout the continent, with northern areas among the fastest warming on the planet. Precipitation trends vary geographically, with a weaker Indian monsoon (WGI AR5 Section 14.2.2.1) and contrasting increasing and drying trends over coastal and inland China (Section 24.3).

Warming has occurred in *Australasia* during the past century, with hot extremes becoming more frequent and cold extremes becoming less

Table 18-8 | Observed impacts of climate change reported since AR4 on coastal and marine ecosystems, over the past several decades, across major world regions, with descriptors for (1) the confidence in detection of a climate change impact; (2) the relative contribution of climate change to the observed change, compared to that of non-climatic drivers; (3) the main climatic driver(s) causing the impacts; (4) the reference behavior of the system in the absence of climate change; and (5) the confidence in attribution of the impacts to climate change. References to related chapters in this report are given as well as key references to other IPCC reports and the scientific literature. Absence of climate change impacts from this table does not imply that such impacts have not occurred.

	Coastal and marine ecosystems	References	Confidence in detection	Role of climate	Climate driver	Reference behavior	Confidence in attribution
Africa	Decline in coral reefs in tropical African waters	Sections 30.5.3.1.2 and 30.5.4.1.5; Baker et al. (2008); Carpenter et al. (2008); Ateweberhan et al. (2011)	*High*	Major	Ocean warming	Decline due to human impacts	*High*
Europe	Northward shifts in the distributions of zooplankton, fish, seabirds, and benthic invertebrates in the northeast Atlantic	Box 6-1; Table 6-2; Sections 6.3.1, 23.6.5, and 30.5.1.1; Beaugrand et al. (2009); Philippart et al. (2011)	*High*	Major	Ocean warming	No change	*High*
	Northward and depth shift in distribution of many fish species across European seas	Sections 6.3.1, 23.6.4, 23.6.5, and 30.5.3.1; Table 6-2; Perry et al. (2005); Pörtner et al. (2008); Beaugrand et al. (2009, 2010); Beaugrand and Kirby (2010); Hermant et al. (2010); Philippart et al. (2011)	*High*	Major	Ocean warming	No change	*Medium*
	Phenology changes in plankton in the northeast Atlantic	Box 6-1; Sections 6.3.1, 23.6.5, and 30.5.1.1; Beaugrand et al. (2002, 2009); Edwards and Richardson (2004); Philippart et al. (2011)	*Medium*	Major	Ocean warming	No change	*Medium*
	Spread of warm water species into the Mediterranean	Sections 23.6.5 and 30.5.3.1.5; Boero et al. (2008); Lasram and Mouillot (2009); Raitsos et al. (2010)	*High*	Major	Ocean warming	Changes due to invasive species and human impacts	*Medium*
Asia	Decline in coral reefs in tropical Asian waters	Sections 24.4.3.2 and 30.5.1.4.3; McLeod et al. (2010); Krishnan et al. (2011); Coles and Riegl (2012)	*High*	Major	Ocean warming	Decline due to human impacts	*High*
	Northward range extension of coral in the East China Sea and western Pacific, and a predatory fish in the Sea of Japan	Section 24.4.3.2; Yamano et al. (2011); Tian et al. (2012); Ogawa-Onishi and Berry (2013)	*Medium*	Major	Ocean warming	No change	*Medium*
	Shift from sardines to anchovies in the western North Pacific	Sections 6.3.1 and 6.3.6; Table 6-2; Takasuka et al. (2007, 2008)	*Medium*	Major	Ocean warming	Fluctuations due to fisheries	*Low*
	Increased coastal erosion in Arctic Asia	Section 24.4.3.2; Razumov (2010); Forbes (2011); Lantuit et al. (2011)	*Medium*	Major	Permafrost degradation, ocean warming, change in sea ice	No change	*Low*
Australasia	Southward shifts in the distribution of marine species near Australia	Table 25-3; Ling et al. (2009b); Pitt et al. (2010); Neuheimer et al. (2011); Wernberg et al. (2011b)	*High*	Major	Ocean warming	Changes due to short-term environmental fluctuations; fishing and pollution	*Medium*
	Change in timing of migration of seabirds in Australia	Section 25.6.2.1; Chambers et al. (2011, 2013a)	*Medium*	Major	Air and ocean warming	No change	*Low*
	Increase in coral bleaching in the Great Barrier Reef and Western Australian Reefs	Sections 6.3.1.4, 6.3.1.5, and 25.6.2.1; Table 25-3; Cooper et al. (2008); De'ath et al. (2009, 2012); Moore et al. (2012)	*High*	Major	Ocean warming	Pollution; physical disturbance	*High*
	Changes in coral disease patterns at Great Barrier Reef	Section 25.6.2.1; Table 25-3; Bruno et al. (2007); Sato et al. (2009); Dalton et al. (2010)	*Medium*	Major	Ocean warming	Pollution	*Medium*
North America	Northward shifts in the distributions of northwest Atlantic fish species	Section 30.5.1.1; Nye et al. (2009, 2011); Lucey and Nye (2010)	*High*	Major	Ocean warming	No change	*High*
	Changes in mussel beds along the west coast of the USA	Smith et al. (2006); Menge et al. (2008); Harley (2011)	*High*	Major	Ocean warming	No change	*High*
	Changes in migration and survival of salmon in the northeast Pacific	Table 6-2; Eliason et al. (2011); Kovach et al. (2012)	*High*	Major	Ocean warming	No change	*High*
	Increased coastal erosion in Alaska and Canada	Sections 18.3.1.1 and 18.3.3.1; Mars and Houseknecht (2007); Forbes (2011); Lantuit et al. (2011)	*High*	Major	Permafrost degradation; ocean warming, change in sea ice	No change	*Medium*

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Table 18-8 (continued)

	Coastal and marine ecosystems	References	Confidence in detection	Role of climate	Climate driver	Reference behavior	Confidence in attribution
South and Central America	Increase in coral bleaching in the western Caribbean	Section 27.3.3.1; Guzman et al. (2008); Manzello et al. (2008); Carilli et al. (2009); Eakin et al. (2010)	*High*	Major	Ocean warming	Pollution; physical disturbance	*High*
	Mangrove degradation on north coast of South America	Section 27.3.3.1; Alongi (2008); Lampis (2010); Polidoro et al. (2010); Giri et al. (2011)	*Low*	Minor	Ocean warming	Degradation due to pollution and land use	*Low*
Polar regions	Increased coastal erosion across the Arctic	Sections 18.3.1.1, 18.3.3.1, 28.2.4.2, and 28.3.4; Mars and Houseknecht (2007); Razumov (2010); Forbes (2011); Lantuit et al. (2011)	*Medium*	Major	Permafrost degradation; ocean warming, change in sea ice	No change	*Medium*
	Negative effects on non-migratory Arctic species	Section 28.2.2.1; Laidre et al. (2008); Amstrup et al. (2010); McIntyre et al. (2011)	*High*	Major	Atmospheric and ocean warming; circulation change; change in sea ice	No change	*High*
	Decreased reproductive success in Arctic seabirds	Section 28.2.2.1.2; Gaston et al. (2009); Grémillet and Boulinier (2009)	*Medium*	Major	Air and ocean warming; change in ocean circulation; change in sea ice	No change	*Medium*
	Decline in Southern Ocean seals and seabirds	Section 28.2.2.2; Croxall et al. (2002); Patterson et al. (2003); Jenouvrier et al. (2005); Véran et al. (2007); Forcada et al. (2008); Trathan et al. (2011); Chambers et al. (2013a)	*High*	Major	Ocean warming	No change	*Medium*
	Reduced thickness of foraminiferal shells in the Southern Ocean	Sections 6.3.2 and 28.2.2.2; Moy et al. (2009)	*Medium*	Major	Ocean acidification	No change	*Medium*
	Reduced density of krill in the Scotia Sea	Atkinson et al. (2004); Trivelpiece et al. (2011)	*Medium*	Major	Ocean warming; change in ocean circulation; change in sea ice	No change	*Medium*
Small islands	Increased coral bleaching near many tropical small islands	Section 29.3.1.2; Alling et al. (2007); Bruno and Selig (2007); Oxenford et al. (2008); Sandin et al. (2008)	*High*	Major	Ocean warming	Degradation due to fishing and pollution	*High*
	Degradation of mangroves, wetlands, and seagrass around small islands	Section 29.3.1.2; McKee et al. (2007); Gilman et al. (2008); Schleupner (2008); Krauss et al. (2010); Marbà and Duarte (2010); Rankey (2011)	*Low*	Minor	Sea level rise; atmospheric and ocean warming	Degradation due to other disturbances	*Very low*
	Increasing flooding and erosion	Section 29.3.1.1; Webb (2006); Webb (2007); Yamano et al. (2007); Cambers (2009); Novelo-Casanova and Suarez (2010); Storey and Hunter (2010); Ballu et al. (2011); Rankey (2011); Ford (2012); Romine et al. (2013)	*Low*	Minor	Sea level rise	Erosion due to human activities, natural erosion, and accretion	*Low*
	Degradation of groundwater and freshwater ecosystems due to saline intrusion	Section 29.3.2; White et al. (2007a,b); Ross et al. (2009); Carreira et al. (2010); Terry and Falkland (2010); White and Falkland (2010); Goodman et al. (2012)	*Low*	Minor	Sea level rise	Degradation due to pollution and groundwater pumping	*Low*

frequent (Section 25.2, Table 25-1). Winters in southern areas of Australia have become drier in the past few decades and the northwest has become wetter, and precipitation increased over the south and west of both islands of New Zealand. Though there have been no significant trends in drought frequency over Australia, regional warming may have increased their hydrological intensity, and fire weather increased since 1973 in Australia (Table 25-1; Clarke et al., 2012).

North America spans a wide range of climate types and observed climate changes. While the northwest has been among the fastest warming regions on the planet, the southeast of the USA has experienced slight cooling (Section 26.2.2.1). Hot extremes have been becoming more frequent while cold extremes and frost days have been becoming less frequent over the past several decades. Trends in precipitation over western parts of the continent are strongly influenced by the variability of the ENSO, with a matching drying and decreasing snowpack. The intensity of precipitation events has been increasing over most of the continent, but trends in dryness are spatially heterogeneous (Section 26.2.2.1). Intense tropical storms have increased in the North Atlantic over the past several decades (WGI AR5 Section 2.6.3).

Most of *Central and South America* has warmed over the past half century, except for a slight cooling over a western coastal strip (Section 27.2.1). Precipitation over much of Central and South America is strongly influenced by the ENSO, with accompanying long-term variability. There has been a reduction in the number of dry summer months in the southern half of the continent, while trends over the Amazon are sensitive to the selection of time period (Section 27.2.1). More frequent and severe droughts in the Amazon have been linked to warming (Marengo et al., 2011a).

The areas of largest observed warming are all *polar*: the northwest of North America, northern Asia, and the Antarctic Peninsula. The nature of polar regions means that warming can lead to large changes in other

Table 18-9 | Observed impacts of climate change reported since AR4 on human and managed systems, over the past several decades, across major world regions, with descriptors for (1) the confidence in detection of a climate change impact; (2) the relative contribution of climate change to the observed change, compared to that of non-climatic drivers; (3) the main climatic driver(s) causing the impacts; (4) the reference behavior of the system in the absence of climate change; and (5) the confidence in attribution of the impacts to climate change. References to related chapters in this report are given as well as key references to other IPCC reports and the scientific literature. Absence of climate change impacts from this table does not imply that such impacts have not occurred.

	Human and managed systems	References	Confidence in detection	Role of climate	Climate driver	Reference behavior	Confidence in attribution
Africa	Adaptative responses to changing rainfall by South African farmers	Section 13.2.1.2; Thomas et al. (2007)	*Low*	Major	Change in precipitation	Changes due to economic conditions	*Very low*
	Decline in fruit-bearing trees in Sahel	Wezel and Lykke (2006); Maranz (2009)	*Medium*	Major	Change in precipitation	No change	*Low*
	Malaria increases in Kenyan highlands	Section 11.5.1.1; O'Meara et al. (2010); Alonso et al. (2011); Stern et al. (2011)	*Low*	Minor	Warming	Changes due to vaccination, drug resistance, demography, and livelihoods	*Low*
	Reduced fisheries productivity of Great Lakes and Lake Kariba	Sections 7.2.1.2, 13.2.1.1, and 22.3.2.2; Descy and Sarmento (2008); Hecky et al. (2010); Ndebele-Murisa et al. (2011); Marshall (2012)	*Low*	Minor	Warming	Changes due to fisheries management and land use	*Low*
Europe	Shift from cold-related mortality to heat-related mortality in England and Wales	Sections 18.4.4 and 23.5.1; Christidis et al. (2010)	*Medium*	Major	Warming	Changes due to exposure and health care	*Low*
	Impacts on livelihoods of Sámi people in northern Europe	Eira (2012); Mathiesen et al. (2013)	*Medium*	Major	Warming	Economic and sociopolitical changes	*Medium*
	Stagnation of wheat yields in some countries in recent decades	Section 23.4.1; Brisson et al. (2010); Kristensen et al. (2011)	*High*	Minor	Warming	Increase due to improved technology	*Medium*
	Positive yield impacts for some crops, mainly in northern Europe	Figure 7-2; Section 23.4.1; Jaggard et al. (2007); Supit et al. (2010); Gregory and Marshall (2012)	*High*	Minor	Warming	Increase due to improved technology	*Medium*
	Spread of bluetongue virus in sheep, and of ticks across parts of Europe	Section 23.4.2; Arzt et al. (2010); Randolph and Rogers (2010); Van Dijk et al. (2010); Guis et al. (2012); Petney et al. (2012)	*High*	Minor	Warming	No change	*Medium*
Asia	Impacts on livelihoods of indigenous groups in Arctic Russia	Sections 13.2.1.2, 18.4.6, and 28.2.4.2; Table 18-4; Crate (2013)	*Medium*	Major	Warming; change in snow cover; change in sea ice	Economic and sociopolitical changes	*Low*
	Negative impacts on aggregate wheat yields in South Asia	Section 7.2.1; Figure 7-2; Pathak et al. (2003)	*Medium*	Minor	Warming; change in precipitation	Increase due to improved technology	*Medium*
	Negative impacts on aggregate wheat and maize yields in China	Section 7.2.1; Figure 7-2; Tao et al. (2006, 2008, 2012); You et al. (2009); Chen et al. (2010)	*Low*	Minor	Warming	Increase due to improved technology	*Low*
	Increases in a water-borne disease in Israel	Paz et al. (2007)	*Low*	Minor	Warming	No change	*Low*
Australasia	Advance timing of wine-grape maturation in recent decades	Table 25-3; Webb et al. (2012)	*High*	Major	Warming	Advance due to improved management	*Medium*
	Shift in winter versus summer human mortality in Australia	Sections 11.4.1, 18.4.4, and 25.8.1.1; Bennett et al. (2013)	*Medium*	Major	Warming	Changes due to exposure and health care	*Low*
	Relocation or diversification of agricultural activities in Australia	Section 25.7.2; Box 25-5; Gaydon et al. (2010); Howden et al. (2010); Park et al. (2012); Thorburn et al. (2012)	*Medium*	Minor	Warming	Changes due to policy, markets, and short-term climate variability	*Low*
Central and South America	More vulnerable livelihood trajectories for indigenous Aymara farmers in Bolivia, due to water shortage	Section 13.1.4; McDowell and Hess (2012)	*Medium*	Major	Warming	Increasing social and economic stress	*Medium*
	Increase in agricultural yields and expansion of agricultural areas in southeastern South America	Section 27.3.4.1; Magrin et al. (2007); Barros (2010); Hoyos et al. (2013)	*Medium*	Major	Precipitation increase	Increase due to improved technology	*Medium*

Continued next page →

Table 18-9 (continued)

	Human and managed systems	References	Confidence in detection	Role of climate	Climate driver	Reference behavior	Confidence in attribution
North America	Impacts on livelihoods of indigenous groups in the Canadian Arctic	Sections 18.4.6 and 28.2.4.2; Table 18-4; Hovelsrud et al. (2008); Ford et al. (2009); Beaumier and Ford (2010); Pearce et al. (2010); Brubaker et al. (2011)	*Medium*	Major	Warming; change in snow cover; change in sea ice	Economic and sociopolitical changes	*Medium*
Polar regions	Impact on livelihoods of Arctic indigenous peoples	Sections 18.4.6 and 28.2.4.2; Table 18-4; Hovelsrud et al. (2008); Ford et al. (2009); Beaumier and Ford (2010); Pearce et al. (2010); Eira (2012); Crate (2013); Mathiesen et al. (2013)	*Medium*	Major	Warming; change in snow cover; change in sea ice	Economic and sociopolitical changes	*Medium*
	Increase of shipping traffic across the Bering Strait	Section 28.2.6.1.3; Figure 28-4; Robards (2013)	*Medium*	Major	Warming; change in sea ice	No change	*Medium*
Small islands	Increased degradation of coastal fisheries due to direct effects and effects of increased coral reef bleaching	Box CC-CR; Sections 18.3.3.3, 18.4.1.2, 29.3.1.2, and 30.6.2.1	*Low*	Minor	Ocean warming	Coastal fisheries degraded by overfishing and pollution	*Low*

aspects of the climate system, in particular the observed decrease in summer sea ice cover, earlier thaw, earlier spring runoff, and thawing of permafrost (Section 28.2).

Despite the widely accepted high vulnerability of many *small islands* to climate change, there are only few formal studies on observed impacts. Detection of climate change impacts in small islands is challenging due to the strong presence of other anthropogenic drivers of local environmental change. Attribution is further challenged by the strong influence of natural variability compared to incremental changes of climate drivers and by the lack of long-term monitoring and high-quality data.

18.6. Synthesis: Emerging Patterns of Observed Impacts of Climate Change

18.6.1. Approach

The AR4 precursor of the current chapter (Rosenzweig et al., 2007) provided a geographically distributed empirical analysis of correlations across numerous detailed and localized studies of changing systems (elaborated more later in Rosenzweig et al., 2008). Rather than expand that approach, this synthesis organizes the findings on detection and attribution of observed impacts of climate change aiming at covering the full disciplinary, sectoral, and geographic diversity of impacts, drawn directly from sectoral and regional assessments in this report.

A key motivation for the effort in assessing these observed changes is the possibility that observed impacts could constitute indications of future expected changes. Observed losses in glacial volume, for example, lend important additional plausibility to model-based expectations that sustained warming could result in additional ice loss. Such extrapolation faces important limitations, however. First, owing to the complex nonlinear behavior of most natural and human systems, it cannot always be assumed that past impacts scale linearly to future impacts. Likewise, absence of past impacts cannot constitute evidence against the possibility of future impacts. Nonetheless, detection and attribution of observed impacts may serve as part of the foundation for a climatic risk analysis. To do so, the total body of observed impacts needs to undergo a synthetic assessment pointing toward any conceivable risks.

Virtually all observed impacts of climate change are of regional nature (Section 18.5); however, the occurrence of similar impacts in many regions of the world emerges more strongly with every IPCC assessment. The global pattern emerging from the sum of observed regional impacts is therefore analyzed in Section 18.6.2. The current body of observations provides improved evidence of major impacts in natural and human systems that have "cascading" consequences for other systems—key examples for these are synthesized in Section 18.6.3. Finally, Section 18.6.4 aims to establish current conditions concerning the risk analysis model formulated earlier by the IPCC through the establishment of a limited number of "Reasons for Concern" (RFC)—the risk analysis itself is part of Chapter 19 of this report.

18.6.2. The Global Pattern of Regional Impacts

The global pattern of observed climate change differs strongly for the different climate variables. Broadly, more warming has occurred at higher latitudes than in the Tropics, while the pattern of rainfall changes is highly complex (WGI AR5 Chapter 2). Taken together, this provides a heterogeneous pattern of climate change across the globe. In addition, some natural and human systems (and the regions in which they occur) are more vulnerable to changing climate than others. Crucially, observational records are of highly heterogeneous nature: not only do low-income countries report fewer impacts than high-income countries, but there is also a significant shortage of observations from remote areas such as the deep sea or sparsely populated mountains and deserts. Taken together, it is therefore natural to expect an uneven distribution of detected impacts (Figure 18-3).

The outstanding finding about the global pattern of observed impacts is that, on all continents and across major ocean regions, significant impacts have now been observed. Many of these concern systems which are affected directly by warming (the cryosphere, marine systems), but a growing number of observed impacts have been shown to be the result of a combination of changing temperature and precipitation (agricultural and hydrological systems).

The global distribution of observed impacts shown in Figure 18-3 demonstrates that analyses can now detect impacts in systems strongly

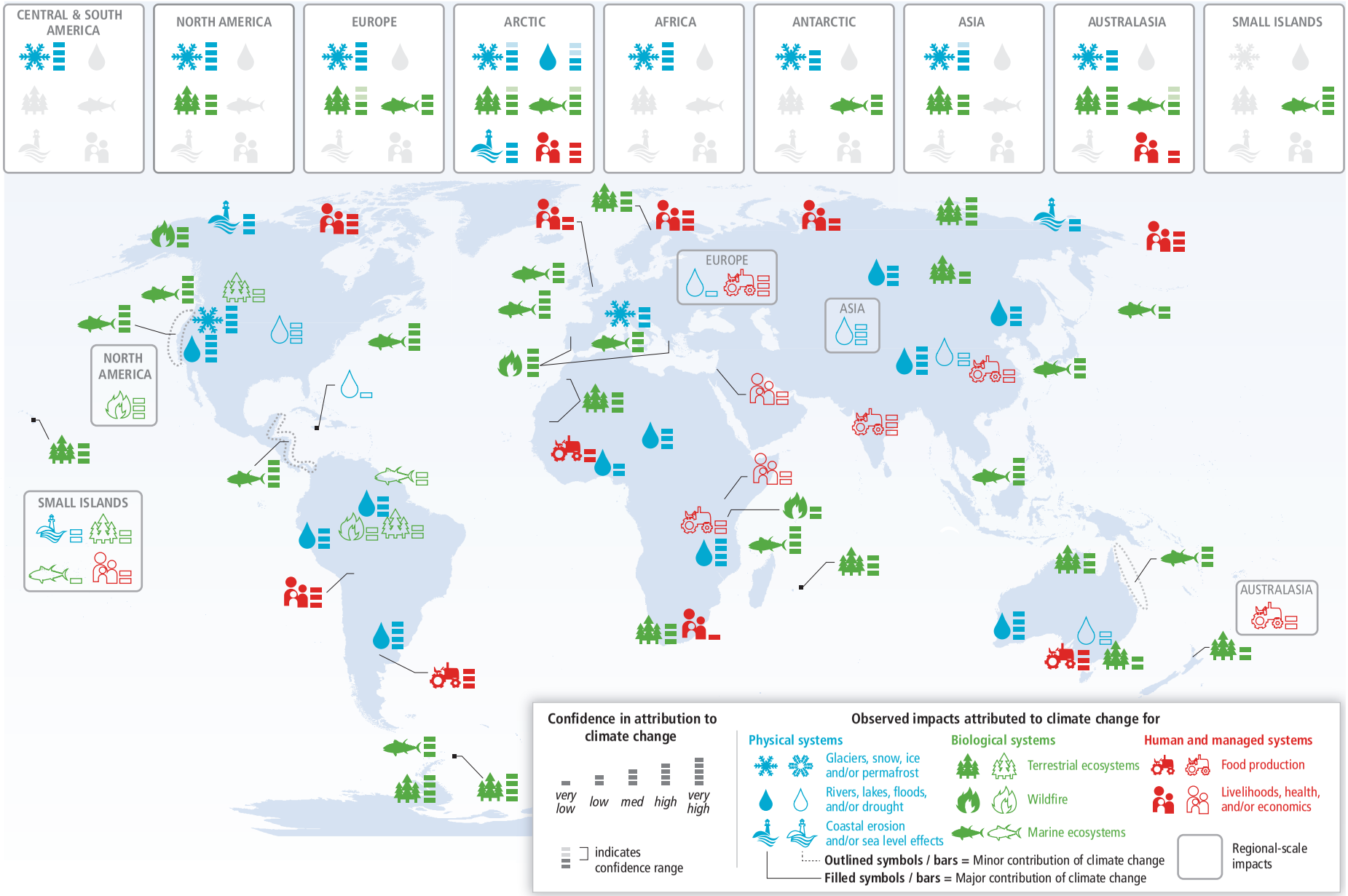

Figure 18-3 | Global patterns of observed climate change impacts reported since AR4. Each filled symbol in the top panels indicates a class of systems for which climate change has played a major role in observed changes in at least one system within that class across the respective region, with the range of confidence in attribution for those region-wide impacts indicated by the bars. Regional-scale impacts where climate change has played a minor role are shown by outlined symbols in a box in the respective region. Sub-regional impacts are indicated with symbols on the map, placed in the approximate area of their occurrence. The impacted area can vary from specific locations to broad areas such as a major river basin. Impacts on physical (blue), biological (green), and human (red) systems are differentiated by color. This map represents a graphical synthesis of Tables 18-5, 18-6, 18-7, 18-8, and 18-9. Absence of climate change impacts from this figure does not imply that such impacts have not occurred.

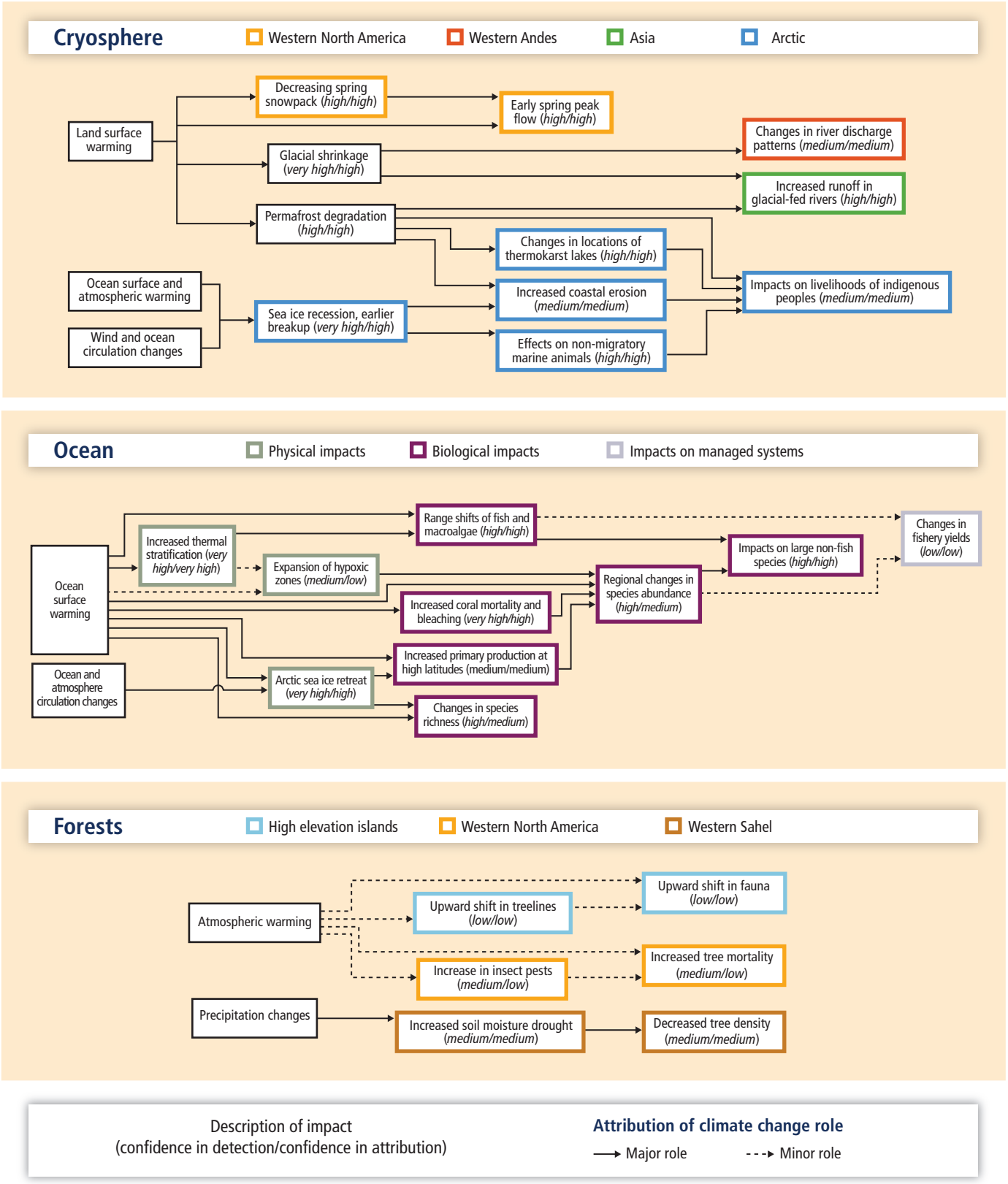

Figure 18-4 | Major systems where new evidence indicates interconnected, "cascading" impacts from recent climate change through several natural and human subsystems. Text in parentheses indicates confidence in the detection of a climate change effect and the attribution of observed impacts to climate change. The role of climate change can be major (solid arrow) or minor (dashed arrow). Confidence is assessed in Sections 18.3, 18.4, 18.5, and 18.6.

influenced by confounding factors and hence where climate change plays only a minor role. The most outstanding examples for this are agricultural systems where impacts now emerge in a number of places. An identified minor role of climate for some impact does not imply that this role is less important. New studies now identify more clearly such roles even when they are masked by stronger confounding factors such as environmental degradation or improved technology. Examples for such studies include assessments of mangrove degradation, caused by both warming and pollution (Giri et al., 2011), or changes in Inuit livelihoods, influenced by both warming and social changes (Ford et al., 2009). Enhanced research efforts would probably add additional observations of impacts with a minor, but important, role of climate to the global map.

18.6.3. Cascading Impacts

Many impacts of climate change are direct cause-effect relationships, such as reduction of glacier volume following higher temperatures. Others may be mediated through impacts on intermediary systems (e.g., Johnson et al., 2011). Enhanced evidence of observed impacts of climate change, and improved research methodologies now allow attribution of effects at various stages along the causal impact chain (Figure 18-4). Within the cryosphere, changes in atmospheric and ocean properties of the climate have driven changes in the cryosphere on the land surface, the land subsurface, and the ocean surface. These changes have in turn led to changes in multiple aspects of hydrology and ecosystems, and in some regions (e.g., the Arctic) changes in these systems have impacted human livelihoods (Xu et al., 2009). Within most ocean regions, warming has led to a number of observed impacts on biota, some of which are mediated through the effect of warming on the ocean's thermal stratification or on sea ice. Impacts tend to propagate up the food chain, eventually affecting large mammals, birds, reptiles, and humans. In forests and woodlands, climate change impacts on trees have been transmitted through pests, fire, and drought, while impacts on forests have also been observed to affect the forest fauna. In all these cases, confidence in detection and attribution to observed climate change decreases for effects further down each impact chain.

18.6.4. Reasons for Concern

To synthesize its findings in support of a risk analysis the IPCC in its Third Assessment Report (TAR) developed the "Reasons for Concern" (RFC) concept (Smith et al., 2001), which was adopted for a second time in IPCC AR4 (IPCC, 2007b), and elaborated in Smith et al. (2009). It is further developed in Chapter 1 of this report and employed extensively in Chapter 19 for the risk framing approach of WGII AR5. In this chapter, the goal is to establish, qualitatively, the evidence of impacts already observed that are relevant to these categories (names of categories have been adapted for consistency across Chapters 1, 18, and 19; see below). The broad definitions of the RFC continue to imply significant overlap; hence some observed impacts are referred to under more than one RFC.

The RFC *Risks to Unique and Threatened Systems* is concerned with the potential for increased damage to, or irreversible loss of, systems such as physical systems, ecosystems, and human livelihoods, all of which are known to be highly sensitive to temporal and/or spatial variations in climate. Figure 18-5 displays confidence levels in the current evidence

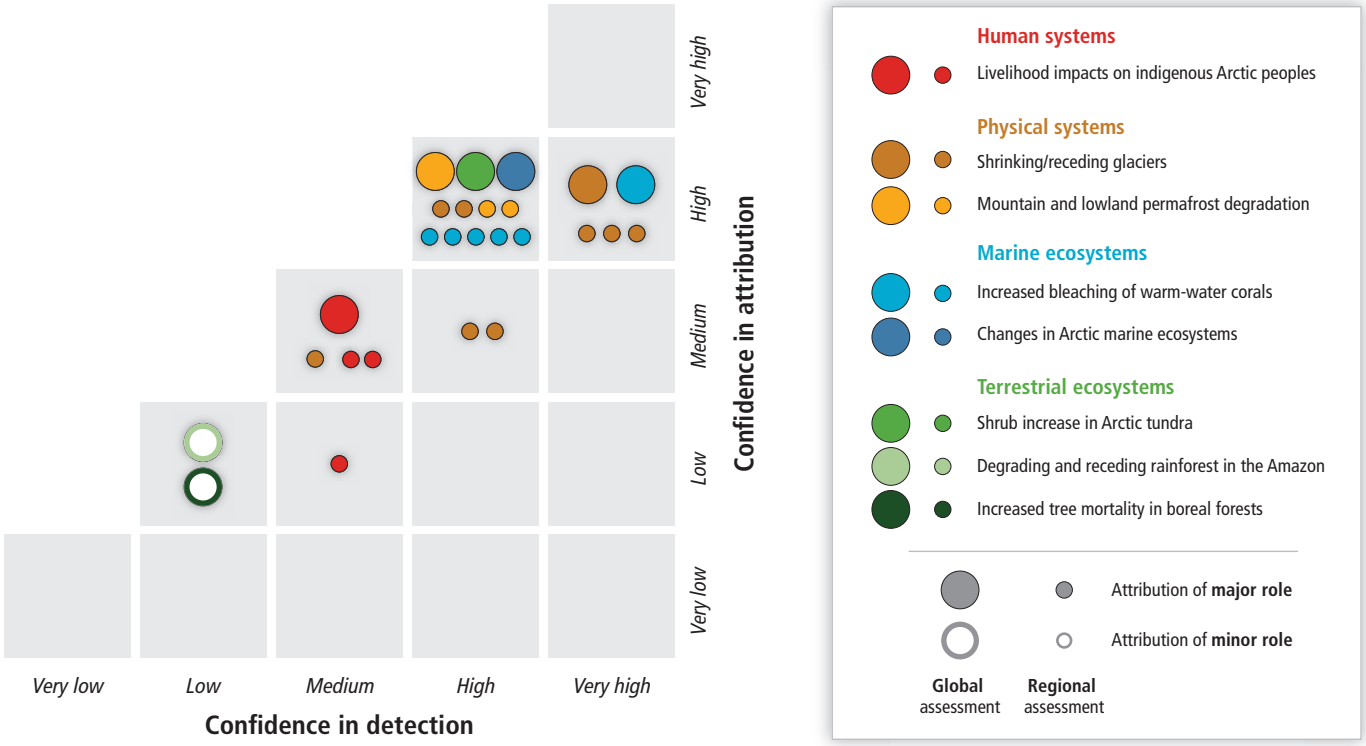

Figure 18-5 | Confidence in detection and attribution of observed impacts on "Unique and Threatened Systems" as a result of recent climate change. Global assessments (large circles) and regional assessments (small circles) are discussed in Sections 18.3.1.1 and 18.3.2.4, Box 18-2, and Tables 18-2 and 18-5 through 18-9. Attribution assessments are for a minor (outlined circles) or major (filled circles) role of climate change, as indicated.

derived from detection and attribution studies of such observed impacts. Changes in the three indicated main natural systems (physical systems, marine and terrestrial ecosystems) have at least *high confidence* in attribution of a major role of climate change, with regional assessments also tending to have similar confidence. There is at least *medium confidence* in attribution of a major role for at least one each of ecosystems, physical systems, and human systems.

The unique and threatened systems with strongest detection and attribution evidence cover the Arctic, warm-water coral reefs, and mountains. In the Arctic, climate change has played a major role in observed impacts on glaciers, permafrost, the tundra, marine ecosystems, and livelihoods of indigenous peoples (at least *medium confidence*), reflecting large-scale changes across both natural and human systems and across the physical and ecological sub-regions. Evidence for the detection and attribution of shrinkage and recession of glaciers comes from all continents, while evidence for attribution of coral bleaching spans a similarly broad area of the tropical oceans (see Figure 18-5).

The RFC *Risks Associated with Extreme Weather Events* "tracks increases in extreme events with substantial consequences for societies and natural systems" (Smith et al., 2009, p. 4134). Besides episodic (e.g., coral bleaching) and chronic (e.g., erosion) impacts of extreme weather events, this RFC also considers increased frequency of extreme impact events (e.g., floods), even if their climate drivers are not wholly episodic in nature. A change in the risk of impacts of extreme weather events could be caused by a change in the probability, intensity, or sequencing of the weather event itself (which are manifestations of recent climate change), or by a change in exposure, vulnerability, or the resilience of the impacted system. Trends have been noted for extreme weather hazards. Temperature extremes have changed in most regions over the past half century, with more frequent hot events and less frequent cold events (*high confidence*; Hansen et al., 2012; Seneviratne et al., 2012; Coumou et al., 2013; see WGI AR5 Section 2.6.1). Some regions have also experienced increasingly frequent periods of heavy precipitation events (*medium confidence*; Min et al., 2011), while other regions have experienced positive or negative trends in measures of dry spells (Seneviratne et al., 2012). Current evidence does not, however, indicate sustained global trends in tropical cyclone or extratropical cyclone activity (Seneviratne et al., 2012; see WGI AR5 Section 2.6.3).

Table 18-10 summarizes new evidence concerning this RFC. Generally, the strongest evidence of detected impacts related to extremes concerns warm-water corals where bleaching has been linked directly to high-temperature spells (Box 18-2; Baker et al., 2008; Strong et al., 2011). Outside of these coral reef systems, however, evidence for extreme event impacts is limited and mostly local. Overall, a number of trends in observed impacts on natural systems have been documented that indicate changing risks driven by changes in extreme weather (*medium confidence*), but any similar trends in human systems have not been detected against large shifts in exposure, vulnerability, and resilience.

Table 18-10 | Confidence in detection and attribution of observed trends in impacts related to extreme weather. The assessment, for the impacts on various systems, is of attribution of those trends to climate change and of the confidence in existence of observed trends in that extreme weather. The assessment of confidence in detection is against the specified reference behavior, while the assessment of attribution is for the indicated minor or major role of observed climate trends. The confidence statements refer to a globally balanced assessment.

Impacts and impact events					Climate/weather drivers		Reference
Observed trend	**Confidence in detection**	**Reference behavior**	**Confidence in attribution**	**Role of climate change**	**Observed trend**	**Confidence in existence of trend**	
Earlier timing and decreasing magnitude of snowmelt floods	*Medium*	No change	*Medium*	Major	Decreasing snow pack	*High*	Section 3.2.7; Tables 18-5 and 18-6; WGI AR5 Section 4.5; Seneviratne et al. (2012)
					Increasing heavy precipitation amounts	*Medium*	
Changes in flood frequency and magnitude in non-snowmelt–fed rivers	*Low*	Changes due to land use	*Low*	Minor	Trends in extreme rainfall amounts	*Medium*	Min et al. (2011); WGI AR5 Sections 2.5.2 and 2.6.2
					Increased evapotranspiration and decreased soil moisture	*Medium*	
Increased coastal erosion in low and mid latitudes	*Very low*	Erosion due to shoreline modification and natural processes	*Very low*	Minor	Increasingly frequent high storm waves and surges	*High*	Sections 5.4.2 and 18.3.3.1; WGI AR5 Section 3.7.5
Increased erosion of Arctic coasts	*Medium*	No change	*Medium*	Major	Lack of sea ice protection from wind storms	*Very high*	Table 18-8; Sections 18.3.1.1, 24.4.3.2, 28.2.4.2, and 28.3.4; Forbes (2011); WGI AR5 Section 4.2.2
Increase in high-mountain rock slope failures	*Low*	No change	*Low*	Major	Increasingly frequent and intense heat waves	*Medium*	Figure 18-2; Huggel et al. (2012a); Seneviratne et al. (2012); Allen and Huggel (2013); WGI AR5 Section 2.6.1
Increased coral bleaching	*Very high*	Changes due to pollution, physical disturbance, and fishing	*High*	Major	Increasingly frequent extreme hot surface waters	*Very high*	Tables 18-2 and 18-8; Sections 5.2.4.2, 6.3.1, 24.4.3.2, 27.3.3.1, 29.3.1.2, 30.3.1.1, and 30.5; Box 18-2
Increased monetary losses	*Low*	Changes due to exposure and wealth	*Low*	Minor	Increased frequency of storms	*Low*	Sections 10.7.3 and 18.4.3.1; Seneviratne et al. (2012); WGI AR5 Section 2.6
					Increased frequency of floods	*Low*	
Increased heat related mortality	*Low*	Changes due to exposure and health care	*Very low*	Minor	Increased frequency of heat waves	*Medium*	Section 11.4.1; Seneviratne et al. (2012);WGI AR5 Section 2.6.1

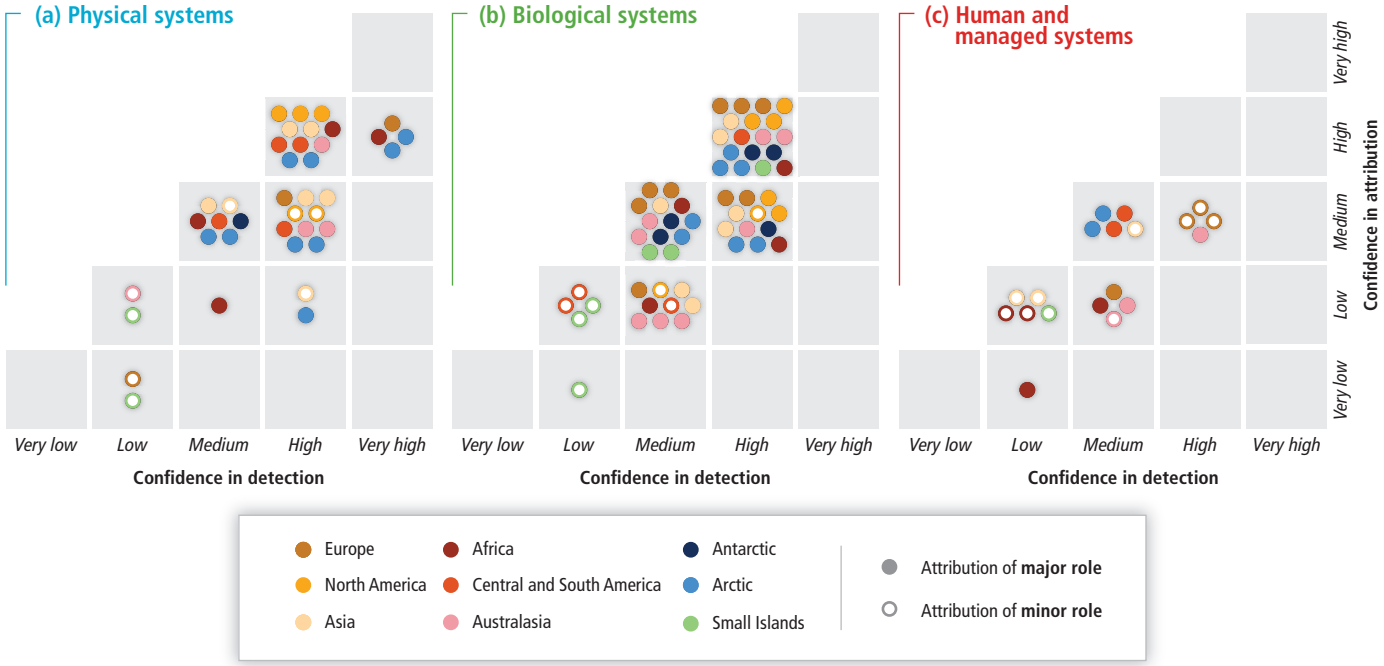

Figure 18-6 | Confidence in detection of observed climate change impacts in physical natural systems, biological systems, and human and managed systems across regions, and confidence in attribution of such trends to observed climate change as a major or minor driver (based on assessments developed in Tables 18-5 to 18-9). (a) Physical systems include the cryosphere, hydrology, and coastal processes; (b) biological systems refer to changes in marine and terrestrial ecosystems, including wildfires; and (c) human and managed systems summarize impacts on food production, health, human livelihoods, and economics.

The RFC *Risks Associated with the Distribution of Impacts* focuses on the disparities of impacts between regions, countries, and populations. The survey of recent studies presented in Section 18.5 indicates that, while evidence for detected impacts is still more exhaustive from Europe and North America, considerable confidence in conclusions has been developed elsewhere since the AR4, particularly in Central and South America and Australasia (Figure 18-3). It is no longer the case that higher confidence levels of detected impacts are restricted to any particular region (Figure 18-6).

The qualitative conclusion that observed impacts on human and managed systems have now been detected with at least *medium confidence* on all inhabited continents is new and noteworthy. However, the number of systems with detectable impacts is only an indicative metric of coverage, because many options exist for aggregation and disaggregation of evidence. Thus this synthesis of detection and attribution studies does not, at this time, provide evidence of differing severity of impacts between continents. Throughout its assessments, the IPCC has repeatedly noted the significant disparity between the vulnerability of countries, regions, and social groups, related to differences in adaptive capacity (e.g., Wilbanks et al., 2007). Nevertheless, additional coverage of detection and attribution studies is required for broad evaluation of social disparities in impacts.

The original intent of the category now labeled as *Risks Associated with Aggregate Impacts* was to assess those economic impacts, damages, and risks that are specifically driven by climate change at a globally aggregated level, using unified monetary metrics. Recognizing the limits of calibrated monetarization of impacts, the scope of this RFC has been expanded over time to also include non-monetary metrics (Smith et al., 2009). Table 18-11 lists various aggregate systems of near-global extent for which the following two conditions apply: there is some form of calibrated metric for comparison of impacts across space and subsystems, and the evidence for detection and attribution of the impacts has sufficient geographical coverage to count as spatially representative sample.

Confidence in such large-scale detection is, again, highest in cryospheric systems (expressed in glacier volume or permafrost active layer thickness), but climate change has also affected ecosystems (expressed as net productivity or carbon stocks, ranging from *medium* to *high confidence*) and some human systems (crop yields, losses due to extreme events, ranging from *low* to *medium confidence*) according to the listed aggregate measures. Thus, several globally aggregated impacts of recent climate change have now been identified.

The RFC *Risks Associated with Large-Scale Singular Events* "represents the likelihood that certain phenomena (sometimes called singularities or tipping points) would occur, any of which may be accompanied by very large impacts" (Smith et al., 2009). Several studies have identified "tipping elements" in the Earth system that exhibit nonlinear behavior with potentially strong feedbacks on the Earth system (Lenton et al., 2008; Leadley et al., 2010). For observed impacts, the concern translates into a question of the possible presence of "early warning signals" for discontinuities that may be derived from monitoring changes in some climate or natural systems (Collie et al., 2004; deYoung et al., 2008; Andersen et al., 2009; Lenton, 2011).

For the Arctic region, new evidence indicates a biophysical regime shift is taking place, with cascading impacts on physical systems, ecosystems, and human livelihoods. For Arctic marine biota, the rapid reduction of summer ice cover causes a tipping element that is now severely

Table 18-11 | Confidence in detection of impacts on aggregate impact measures against the specified reference behavior and confidence in attribution of the specified role of climate change in those observed changes.

Global aggregated impact	Confidence in detection	Reference behavior	Confidence in attribution	Role of climate change	Reference
Glacier ice volume reduction	*Very high*	No change	*High*	Major	Sections 3.2.2 and 18.3.1.1
Permafrost degradation and increase of active layer thickness	*High*	No change	*High*	Major	Section 18.3.1.1
Increase in terrestrial net primary production and carbon stocks	*High*	Changes due to nitrogen deposition, afforestation, and land management	*Low*	Major	Section 18.3.2.2
Negative yield impacts on global wheat and maize yields	*Medium*	Changes due to technology, practice, and coverage	*Medium*	Minor	Section 18.4.1.1; Figure 7-2
Increase in monetary losses due to extreme weather	*Low*	Changes due to exposure and wealth	*Low*	Minor	Sections 10.7.3 and 18.4.3.1

affecting pelagic ecosystems as well as ice-dependent mammals such as seals and polar bears (*high confidence*; Duarte et al., 2012a; see also Tables 18-2, 18-8; Section 28.2.2.1). On land, thawing of Arctic permafrost and shrub encroachment on the tundra have been driven by warming and prolongation of the growing season (*high confidence*; Sections 4.3.3.4, 18.3.2.4, 24.4.2.2; Tables 18-5, 18-7; Figure 4-4). Permafrost degradation has contributed to widespread hydrological changes including lake formation or disappearance within a few years' time (*high confidence*; Prowse and Brown, 2010; Callaghan et al., 2013; Table 18-6), while increasing winter rains have had consequences for the tundra food webs (*medium confidence*; Post et al., 2009; Callaghan et al., 2013; Hansen et al., 2013). Indigenous people throughout the Arctic are impacted by these changes (Eira, 2012; Crate, 2013; see also Section 18.4.6). In summary, several indicators of the ongoing regime shift in the entire Arctic land-sea socio-ecological system can be interpreted as a warning sign for a large-scale singular event (Post et al., 2009; CAFF, 2010; Callaghan et al., 2010; AMAP, 2011; Duarte et al., 2012b; Figure 18-3; Tables 18-5, 18-7 to 18-9; Section 28.2).

Reef building corals are in rapid decline in many regions, and climate change is one of the major drivers (*high confidence*; Box 18-2). This irreversible loss of biodiversity has significant feedbacks within the marine biosphere, and significant consequences for regional marine ecosystems as well as the human livelihoods that depend on them (Hoegh-Guldberg and Bruno, 2010; Richardson et al., 2012). The growing evidence for presently ongoing change and its attribution to warming gained since the AR4 strengthens the conclusion that increased mass bleaching of corals constitutes a strong warning signal for the singular event that would constitute the irreversible loss of an entire biome.

Dieback and degradation in the boreal forests as well as the Amazonian rainforest have also been identified as potential tipping elements in the Earth system, due to their large extent and the possible feedbacks with the carbon cycle (Lenton et al., 2008; Leadley et al., 2010; Marengo et al., 2011b; see also Section 4.3.3.1). For the boreal forest, increases in tree mortality have been observed in many regions, including widespread dieback related to insect infestations and fire in North America (Sections 4.3.3.1, 26.4.2.1). Taken together, these may be seen as indicators of an ongoing regime shift in the boreal forest, but there is only *low confidence* in attribution to climate change (Section 18.3.2.4; Figure 4-4). In the humid tropical forests of the Amazon basin, increased tree turnover (both mortality and growth) and enhanced drought risks have been observed during recent decades. However, the main reason for concern is the interaction between climate change, deforestation, and the high susceptibility of forests to fire, which together could produce positive feedbacks leading to degradation of forests in large areas of the Amazon (Malhi et al., 2009). Currently, there is only *low confidence* in attribution of observed ecosystem changes in the Amazon to climate change. In conclusion, there is insufficient evidence from observed climate change impacts to support a climate-related warning sign of possible large-scale singular events in the boreal and Amazonian forest.

18.6.5. Conclusion

Detection and attribution studies evaluate the agreement between observations of change in a system and process understanding of its causes, whether these are due to climate change or other forces. This sets a higher bar for establishing confidence in the assessment of past changes than is generally applied to the projections of future changes, because observational evidence has important gaps, while plausibility of future changes is established on the basis of process knowledge only. Despite this constraint, the body of evidence on observed impacts of recent climate change demonstrates increasing coverage of the Earth and its various subsystems, including human livelihoods. Increasingly, there is also evidence for complex changes in interconnected systems.

This analysis lends new qualitative support to four out of the five RFCs established by earlier IPCC assessments. Specifically, evidence is notable for risks to unique and threatened systems, risks stemming from extreme weather events, risks associated with globally aggregated impacts, and—in terms of early warnings—risks associated with large-scale discontinuities. Only the spatial or social disparities covered under "Risks Associated with the Distribution of Impacts" are still insufficiently studied to permit a synthesis of available observations for the characterization of a global concern. While the Arctic stands out as a region with *robust evidence* of impacts across numerous systems, current detection and attribution literature does not address whether the severity of those impacts differs from other regions. The Arctic region, warm-water coral reef systems, and mountain glaciers feature strongly in the observational evidence discussed for all the RFCs, but there are also important observations from impacted hydrological systems and human systems, including agriculture.

The evidence gathered since the AR4 on detection and attribution of observed impacts from climate change has reached a level at which it can inform evaluation of many of the aspects of present-day climate change risk as described by the RFCs. In particular, the geographical

distribution of studies is reaching the point where assessment of the global nature of impacts is possible:

- There is now *robust evidence* of observed changes in natural systems in all of the regional groupings used in this report. Climate change has played a major role in observed changes in various components of the cryosphere on all continents (*high confidence*). Climate change has also driven observed changes in terrestrial ecosystems on six continents (*high confidence*, the exception being *low confidence* in Central and South America) and on some small islands (*medium confidence*), and for marine ecosystems surrounding six continents and some small islands (*high confidence*, with evidence lacking for Africa).
- There is *new and stronger evidence* of the detection of impacts in human systems on the inhabited continents. There is at least *medium confidence* in detection of impacts on food production in all the inhabited continents except North America.
- While the current detection and attribution literature does not reveal observational evidence of geographical differences in the severity of climate change impacts between continents, it does indicate that the unique systems of the Arctic region and warm water coral reefs are undergoing rapid changes in response to observed warming in ways that are potentially irreversible.

18.7. Gaps, Research Needs, and Emerging Issues

There are three broad areas relating to the detection and attribution of the impacts of climate change on natural and human systems that require more research. The first concerns the formulation of the relevant issues and further development of rigorous scientific methods for addressing them. At present, the terms detection and attribution are used in numerous different ways, and, while there is no need for a single definition, more clarity about usage is important. Methods in this area are closely linked to specific formulations of these terms and there is a parallel need to develop, refine, and evaluate them in light of this. For example, statistical methods are commonly used to detect the impact of variations in climate on human and natural systems while controlling for the effect of other factors. Such detection can be valuable in helping to predict the response of systems to projections of future climate change but a positive correlation does not necessarily imply that the system has already changed in response to historical climate change. A second example is the growing use of methods that combine information from multiple systems— for example, different locations or species— to draw a conclusion about systems in general. More conceptual work is needed to develop the basis for such ecological meta-analysis and the interpretation of its results.

A second area in which more work is needed is data collection and monitoring. Globally, environmental data are still insufficient for monitoring the impacts of climate change. In addition, developed countries are typically over-represented in impact studies because of their comparable wealth in socioeconomic data. Because the level of economic development is extremely important in determining the impacts of climate change, this over-representation probably gives rise to a distorted picture of the global impacts of climate change.

Finally, this chapter stresses the need to base detection and attribution studies on a scientific understanding of the system in question and the way in which climate change (and other factors) might affect it rather than on relatively simple correlational analysis. This is particularly important for human systems and at least some natural systems in which the combined effect of climate change and other factors is complex and historical adaptation to climate change must be expected. Further development, refinement, and evaluation of both conceptual and process-based models of the human-environment system will be essential for improved conclusions about detection and attribution.

Frequently Asked Questions

FAQ 18.1 | Why are detection and attribution of climate impacts important?

To respond to climate change, it is necessary to predict what its impacts on natural and human systems will be. As some of these predicted impacts are expected to already have occurred, detection and attribution provides a way of validating and refining predictions about the future. For example, one of the clearest predicted ecological impacts of climate is a poleward shift in the ranges of plant and animal species. The detection in historical data of a climate-related shift in species ranges would lend credence to this prediction, and the assessment of its magnitude would provide information about the likely magnitude of future shifts.

Frequently Asked Questions

FAQ 18.2 | Why is it important to assess impacts of all climate change aspects, and not only impacts of anthropogenic climate change?

Natural and human systems are affected by both natural and anthropogenic climate change, operating locally, regionally, and/or globally. To understand the sensitivity of natural and human systems to expected future climate change, and to anticipate the outcome of adaptation policies, it is less important whether the observed changes have been caused by anthropogenic climate change or by natural climate fluctuations. In the context of this chapter, all known impacts of climate change are assessed.

Frequently Asked Questions

FAQ 18.3 | What are the main challenges in detecting climate change impacts?

The detection of climate change impacts addresses the question of whether a system has changed beyond its expected behavior in the absence of climate change. This requires an understanding of both the external and internal factors that affect the system. External factors that can affect natural systems include exploitation, land use changes, and pollution. Even in the absence of changes in external factors, many natural systems exhibit substantial internal variability—such as booms and busts in wild populations—that can last for long periods. For example, to detect the impact of climate change on wild fish stocks, it is necessary to understand the effects of fishing, habitat alteration, and possibly pollution, as well as the internal stock dynamics. In the same way, human systems are affected by social and economic factors that are unrelated to climate change. For example, to detect the impact of climate change on human health, it is necessary to understand the effects of changes in public health measures such as improved sanitation.

Frequently Asked Questions

FAQ 18.4 | What are the main challenges in attributing changes in a system to climate change?

Whereas the detection of climate change impacts addresses the question only of whether or not a system has changed as a result of climate change, attribution addresses the magnitude of the contribution of climate change to such changes. Even when it is possible to detect the impact of climate change on a system, more detailed understanding may be needed to assess the magnitude of this impact in relation to the influences of other external factors and natural variability.

Frequently Asked Questions

FAQ 18.5 | Is it possible to attribute a single event, like a disease outbreak or the extinction of a species, to climate change?

It is possible to detect trends in the frequency or characteristics of a class of weather events like heat waves. Similarly, trends in a certain kind of impact of that class of events can also be detected and attributed, although the influence of other drivers of change, such as policy decisions and increasing wealth, can make this challenging. However, any single impact event also results from the antecedent conditions of the impacted system. Thus though damage from a single extreme weather event may occur against the background of trends in many influencing factors, including climate change, there is always a contribution from random chance.

References

ACIA, 2005: *Arctic Climate Impact Assessment.* Cambridge University Press, New York, NY, USA, 1042 pp.

Adamík, P. and M. Král, 2008: Climate-and resource-driven long-term changes in dormice populations negatively affect hole-nesting songbirds. *Journal of Zoology*, **275(3)**, 209-215.

Adano, W.R., T. Dietz, K. Witsenburg, and F. Zaal, 2012: Climate change, violent conflict and local institutions in Kenya's drylands. *Journal of Peace Research*, **49**, 65-80.

Adelekan, I.O., 2010: Vulnerability of poor urban coastal communities to flooding in Lagos, Nigeria. *Environment and Urbanization*, **22(2)**, 433-450.

Adrian, R., C.M. O'Reilly, H. Zagarese, S.B. Baines, D.O. Hessen, W. Keller, D.M. Livingstone, R. Sommaruga, D. Straile, and E. Van Donk, 2009: Lakes as sentinels of climate change. *Limnology and Oceanography*, **54(6)**, 2283-2297.

Agrawal, A., 1995: Dismantling the divide between indigenous and scientific knowledge. *Development and Change*, **26(3)**, 413-439.

Akpinar-Ferrand, E. and A. Singh, 2010: Modeling increased demand of energy for air conditioners and consequent CO_2 emissions to minimize health risks due to climate change in India. *Environmental Science & Policy*, **13(8)**, 702-712.

Alderman, H., 2010: Safety nets can help address the risks to nutrition from increasing climate variability. *The Journal of Nutrition*, **140(1)**, 148-152.

Alexander, C., N. Bynum, E. Johnson, U. King, T. Mustonen, P. Neofotis, N. Oettle, C. Rosenzweig, C. Sakakibara, V. Shadrin, M. Vicarelli, J. Waterhouse, and B. Weeks, 2011: Linking indigenous and scientific knowledge of climate change. *BioScience*, **61**, 477-484.

Alheit, J., T. Pohlmann, M. Casini, W. Greve, R. Hinrichs, M. Mathis, K. O'Driscoll, R. Vorberg, and C. Wagner, 2012: Climate variability drives anchovies and sardines into the North and Baltic Seas. *Progress in Oceanography*, **96(1)**, 128-139.

Ali, T., B. Shahbaz, and A. Suleri, 2006: Analysis of myths and realities of deforestation in Northwest Pakistan: implications for forestry extension. *International Journal of Agriculture and Biology*, **8(1)**, 107-110.

Allen, M., 2011: In defense of the traditional null hypothesis: remarks on the Trenberth and Curry WIREs opinion articles. *Wiley Interdisciplinary Reviews: Climate Change*, **2**, 931-934.

Allen, S. and C. Huggel, 2013: Extremely warm temperatures as a potential cause of recent high mountain rockfall. *Global and Planetary Change*, **107(8)**, 59-69.

Allen, S.K., S.C. Cox, and I.F. Owens, 2010: Rock-avalanches and other landslides in the central Southern Alps of New Zealand: a regional assessment of possible climate change impacts. *Landslides*, **8(1)**, 33-48.

Alling, A., O. Doherty, H. Logan, L. Feldman, and P. Dustan, 2007: Catastrophic coral mortality in the remote central Pacific Ocean: Kiribati Phoenix Islands. In: *Atoll Research Bulletin*. No. 551, National Museum of Natural History, Smithsonian Institution, Washington, DC, USA, 21 pp.

Alongi, D.M., 2008: Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. *Estuarine Coastal and Shelf Science*, **76(1)**, 1-13.

Alonso, D., M.J. Bouma, and M. Pascual, 2011: Epidemic malaria and warmer temperatures in recent decades in an East African highland. *Proceedings of the Royal Society B*, **278**, 1661-1669.

Alston, M., 2011: Gender and climate change in Australia. *Journal of Sociology*, **47(1)**, 53-70.

Álvarez-Berríos, N.L., I.K. Parés-Ramos, and T.M. Aide, 2013: Contrasting patterns of urban expansion in Colombia, Ecuador, Peru, and Bolivia between 1992 and 2009. *Ambio*, **42(1)**, 29-40.

AMAP, 2011: *Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere.* Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, 538 pp.

Amstrup, S.C., E.T. DeWeaver, D.C. Douglas, B.G. Marcot, G.M. Durner, C.M. Bitz, and D.A. Bailey, 2010: Greenhouse gas mitigation can reduce sea-ice loss and increase polar bear persistence. *Nature*, **468(7326)**, 955-958.

Amthor, J.S., 2001: Effects of atmospheric CO_2 concentration on wheat yield. Review of results from experiments using various approaches to control CO_2 concentration. *Field Crops Research*, **73(1)**, 1-34.

Andersen, T., J. Carstensen, E. Hernández-García, and C.M. Duarte, 2009: Ecological thresholds and regime shifts: approaches to identification. *Trends in Ecology & Evolution*, **24(1)**, 49-57.

Anderson, C.A., 1987: Temperature and aggression: effects on quarterly, yearly, and city rates of violent and nonviolent crime. *Journal of Personality and Social Psychology*, **52(6)**, 1161-1173.

Anderson, C.A., 2001: Heat and violence. *Current Directions in Psychological Sciences*, **10(1)**, 33-38.

Andreassen, L.M., B. Kjollmoen, A. Rasmussen, K. Melvold, and O. Nordli, 2012: Langfjordjokelen, a rapidly shrinking glacier in northern Norway. *Journal of Glaciology*, **58(209)**, 581-593.

Aporta, C., D.R.F. Taylor, and G.J. Laidler, 2011: Geographies of Inuit sea ice use. Introduction. *Canadian Geographer / Le Géographe Canadien*, **55**, 1-5.

Arctic Council, 2013: *Arctic Resilience Interim Report 2013.* Stockholm Environment Institute (SEI) and Stockholm Resilience Centre, Stockholm, Sweden, 117 pp.

Ariano, R., G.W. Canonica, and G. Passalacqua, 2010: The possible role of climate changes in variations of pollen seasons and allergic sensitizations over 27 years. *The Journal of Allergy and Clinical Immunology*, **125(2 Suppl. 1)**, AB192, doi:10.1016/j.jaci.2009.12.753.

Armah, F.A., J.O. Odoi, G.T. Yengoh, S. Obiri, D.O. Yawson, and E.K.A. Afrifa, 2011: Food security and climate change in drought-sensitive savanna zones of Ghana. *Mitigation and Adaptation Strategies for Global Change*, **16(3)**, 291-306.

Arora-Jonsson, S., 2011: Virtue and vulnerability: discourses on women, gender and climate change. *Global Environmental Change*, **21(2)**, 744-751.

Arrigo, K.R. and G.L. Van Dijken, 2011: Secular trends in Arctic Ocean net primary production. *Journal of Geophysical Research*, **116(C9)**, C09011, doi:10.1029/2011JC007151.

Artur, L. and D. Hilhorst, 2012: Everyday realities of climate change adaptation in Mozambique. *Global Environmental Change*, **22(2)**, 529-536.

Arzt, J., W.R. White, B.V. Thomsen, and C.C. Brown, 2010: Agricultural diseases on the move early in the third millennium. *Veterinary Pathology Online*, **47(1)**, 15-27.

Ateweberhan, M., T. McClanahan, N. Graham, and C. Sheppard, 2011: Episodic heterogeneous decline and recovery of coral cover in the Indian Ocean. *Coral Reefs*, **30(3)**, 739-752.

Atkinson, A., V. Siegel, E. Pakhomov, and P. Rothery, 2004: Long-term decline in krill stock and increase in salps within the Southern Ocean. *Nature*, **432(7013)**, 100-103.

Auffhammer, M. and J.R. Vincent, 2012: Unobserved time effects confound the identification of climate change impacts. *Proceedings of the National Academy of Sciences of the United States of America*, **109(30)**, 11973-11974.

Auffhammer, M., V. Ramanathan, and J.R. Vincent, 2006: Integrated model shows that atmospheric brown clouds and greenhouse gases have reduced rice harvests in India. *Proceedings of the National Academy of Sciences of the United States of America*, **103(52)**, 19668-19672.

Axford, Y., J.P. Briner, C.A. Cooke, D.R. Francis, N. Michelutti, G.H. Miller, J.P. Smol, E.K. Thomas, C.R. Wilson, and A.P. Wolfe, 2009: Recent changes in a remote Arctic lake are unique within the past 200,000 years. *Proceedings of the National Academy of Sciences of the United States of America*, **106(44)**, 18443-18446.

Ayyappan, R., S. Sankar, P. Rajkumar, and K. Balakrishnan, 2009: Work-related heat stress concerns in automotive industries. A case study from Chennai, India. *Global Health Action*, **2**, doi:10.3402/gha.v2i0.2060.

Badjeck, M.C., E.H. Allison, A.S. Halls, and N.K. Dulvy, 2010: Impacts of climate variability and change on fishery-based livelihoods. *Marine Policy*, **34(3)**, 375-383.

Bajracharya, S.R. and P. Mool, 2009: Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal. *Annals of Glaciology*, **50(53)**, 81-86.

Baker, A.C., P.W. Glynn, and B. Riegl, 2008: Climate change and coral reef bleaching: an ecological assessment of long-term impacts, recovery trends and future outlook. *Estuarine, Coastal and Shelf Science*, **80(4)**, 435-471.

Balakrishnan, K., A. Ramalingam, V. Dasu, J.C. Stephen, M.R. Sivaperumal, D. Kumarasamy, K. Mukhopadhyay, S. Ghosh, and S. Sambandam, 2010: Case studies on heat stress related perceptions in different industrial sectors in southern India. *Global Health Action*, **3**, 5635, doi:10.3402/gha.v3i0.5635.

Ballantyne, C.K., 2002: Paraglacial geomorphology. *Quaternary Science Reviews*, **21(18-19)**, 1935-2017.

Ballu, V., M.N. Bouin, P. Siméoni, W.C. Crawford, S. Calmant, J.M. Boré, T. Kanas, and B. Pelletier, 2011: Comparing the role of absolute sea-level rise and vertical tectonic motions in coastal flooding, Torres Islands (Vanuatu). *Proceedings of the National Academy of Sciences of the United States of America*, **108(32)**, 13019-13022.

Banfai, D.S. and D. Bowman, 2007: Drivers of rain-forest boundary dynamics in Kakadu National Park, Northern Australia. A field assessment. *Journal of Tropical Ecology*, **23**, 73-86.

Baraer, M., B.G. Mark, J.M. McKenzie, T. Condom, J. Bury, K.I. Huh, C. Portocarrero, J. Gómez, and S. Rathay, 2012: Glacier recession and water resources in Peru's Cordillera Blanca. *Journal of Glaciology*, **58(207)**, 134-150.

Barange, M. and R.I. Perry, 2009: Physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture. In: *Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge* [Cochrane, K., C. de Young, D. Soto, and T. Bahri (eds.)]. FAO Fisheries and Aquaculture Technical Paper No. 530, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, pp. 7-106.

Barlow, P.M. and E.G. Reichard, 2010: Saltwater intrusion in coastal regions of North America. *Hydrogeology Journal*, **18(1)**, 247-260.

Barnett, T.P., D.W. Pierce, H.G. Hidalgo, C. Bonfils, B.D. Santer, T. Das, G. Bala, A.W. Wood, T. Nozawa, A.A. Mirin, D.R. Cayan, and M.D. Dettinger, 2008: Human-induced changes in the hydrology of the western United States. *Science*, **319(5866)**, 1080-1080.

Barnosky, A.D., N. Matzke, S. Tomiya, G.O. Wogan, B. Swartz, T.B. Quental, C. Marshall, J.L. McGuire, E.L. Lindsey, and K.C. Maguire, 2011: Has the Earth's sixth mass extinction already arrived? *Nature*, **471(7336)**, 51-57.

Barredo, J.I., 2010: No upward trend in normalised windstorm losses in Europe: 1970-2008. *Natural Hazards and Earth System Sciences*, **10**, 97-104.

Barredo, J.I., D. Saurí, and M.C. Llasat, 2012: Assessing trends in insured losses from floods in Spain 1971-2008. *Natural Hazards Earth System Sciences*, **12**, 1723-1729.

Barriopedro, D., E.M. Fischer, J. Luterbacher, R.M. Trigo, and R. García-Herrera, 2011: The hot summer of 2010: redrawing the temperature record map of Europe. *Science*, **332(6026)**, 220-224.

Barrios, S., L. Bertinelli, and E. Strobl, 2006: Climatic change and rural-urban migration. The case of sub-Saharan Africa. *Journal of Urban Economics*, **60(3)**, 357-371.

Barros, V.R., 2010: Capítulo 3: El cambio climático en Argentina. In: *Agro y Ambiente: Una Agenda Compartida para el Desarrollo Sustentable.* Foro de la Cadena Agroindustrial Argentina, Buenos Aires, Argentina, 35 pp., www.foroagroindustrial.org.ar/pdf/cap3.pdf.

Barthel, F. and E. Neumayer, 2012: A trend analysis of normalized insured damage from natural disasters. *Climatic Change*, **113(2)**, 215-237.

Bauder, A., M. Funk, and M. Huss, 2007: Ice-volume changes of selected glaciers in the Swiss Alps since the end of the 19th century. *Annals of Glaciology*, **46(1)**, 145-149.

Beaugrand, G. and R.R. Kirby, 2010: Climate, plankton and cod. *Global Change Biology*, **16(4)**, 1268-1280.

Beaugrand, G., P.C. Reid, F. Ibanez, J.A. Lindley, and M. Edwards, 2002: Reorganization of North Atlantic marine copepod biodiversity and climate. *Science*, **296(5573)**, 1692-1694.

Beaugrand, G., C. Luczak, and M. Edwards, 2009: Rapid biogeographical plankton shifts in the North Atlantic Ocean. *Global Change Biology*, **15(7)**, 1790-1803.

Beaugrand, G., M. Edwards, and L. Legendre, 2010: Marine biodiversity, ecosystem functioning, and carbon cycles. *Proceedings of the National Academy of Sciences of the United States of America*, **107(22)**, 10120-10124.

Beaumier, M. and J.D. Ford, 2010: Food insecurity among Inuit women exacerbated by socio-economic stresses and climate change. *Canadian Journal of Public Health*, **101(3)**, 196-201.

Beck, P.S. and S.J. Goetz, 2011: Satellite observations of high northern latitude vegetation productivity changes between 1982 and 2008: ecological variability and regional differences. *Environmental Research Letters*, **6(4)**, 045501, doi:10.1088/1748-9326/6/4/045501.

Becken, S. and J. Hay, 2007: *Tourism and Climate Change: Risks and Opportunities.* Channel View Publications, Bristol, UK, 289 pp.

Bednaršek, N., G.A. Tarling, D.C.E. Bakker, S. Fielding, E.M. Jones, H.J. Venables, P. Ward, A. Kuzirian, B. Lézé, R.A. Feely, and E.J. Murphy, 2012: Extensive dissolution of live pteropods in the Southern Ocean. *Nature Geoscience*, **5**, 881-885.

Behrenfeld, M.J., R.T. O'Malley, D.A. Siegel, C.R. McClain, J.L. Sarmiento, G.C. Feldman, A.J. Milligan, P.G. Falkowski, R.M. Letelier, and E.S. Boss, 2006: Climate-driven trends in contemporary ocean productivity. *Nature*, **444(7120)**, 752-755.

Belkin, I.M., 2009: Rapid warming of large marine ecosystems. *Progress in Oceanography*, **81(1-4)**, 207-213.

Bell, G.D., E. Blake, K.C. Mo, C.W. Landsea, R. Pasch, M. Chelliah, S.B. Goldenberg, and H.J. Diamond, 2006: The record breaking 2005 Atlantic hurricane season. In: *State of the Climate in 2005* [Shein, K.A. (ed.)]. Special Supplement to the *Bulletin of the American Meteorological Society*, **87(6 Suppl.)**, S44-S45.

Beniston, M., M. Stoffel, and M. Hill, 2011: Impacts of climatic change on water and natural hazards in the Alps: can current water governance cope with future challenges? Examples from the European "ACQWA" project. *Environmental Science & Policy*, **14(7)**, 734-743.

Bennett, C.M., K.G.B. Dear, and A.J.C. McMichael, 2013: Shifts in the seasonal distribution of deaths in Australia, 1968-2007. *International Journal of Biometeorology* (in press), doi:10.1007/s00484-013-0663-x.

Benning, T.L., D. LaPointe, C.T. Atkinson, and P.M. Vitousek, 2002: Interactions of climate change with biological invasions and land use in the Hawaiian Islands: modeling the fate of endemic birds using a geographic information system. *Proceedings of the National Academy of Sciences of the United States of America*, **99(22)**, 14246-14249.

Benson, B.J., J.J. Magnuson, O.P. Jensen, V.M. Card, G. Hodgkins, J. Korhonen, D.M. Livingstone, K.M. Stewart, G.A. Weyhenmeyer, and N.G. Granin, 2012: Extreme events, trends, and variability in Northern Hemisphere lake-ice phenology (1855-2005). *Climatic Change*, **112(2)**, 299-323.

Berkes, F., 2009: Indigenous ways of knowing and the study of environmental change. *Journal of the Royal Society of New Zealand*, **39**, 151-156.

Bertrand, R., J. Lenoir, C. Piedallu, G. Riofrío-Dillon, P. de Ruffray, C. Vidal, J. Pierrat, and J. Gégout, 2011: Changes in plant community composition lag behind climate warming in lowland forests. *Nature*, **479(7374)**, 517-520.

Beven, J.L., L.A. Avila, E.S. Blake, D.P. Brown, J.L. Franklin, R.D. Knabb, R.J. Pasch, J.R. Rhome, and S.R. Stewart, 2008: Atlantic hurricane season of 2005. *Monthly Weather Review*, **136(3)**, 1109-1173.

Biasutti, M. and A. Giannini, 2006: Robust Sahel drying in response to late 20th century forcings. *Geophysical Research Letters*, **33(11)**, L11706, doi:10.1029/2006GL026067.

Birdsey, R., K. Pregitzer, and A. Lucier, 2006: Forest carbon management in the United States. *Journal of Environmental Quality*, **35(4)**, 1461-1469.

Björk, R.G. and U. Molau, 2007: Ecology of alpine snow beds and the impact of global change. *Arctic, Antarctic and Alpine Research*, **39(1)**, 34-43.

Björnsson, H. and F. Pálsson, 2008: Icelandic glaciers. *Jökull*, **58**, 365-386.

Black, R., W.N. Adger, N.W. Arnell, S. Dercon, A. Geddes, and D. Thomas, 2011: The effect of environmental change on human migration. *Global Environmental Change*, **21(Suppl. 1)**, 3-11.

Blok, D., U. Sass-Klaassen, G. Schaepman-Strub, M. Heijmans, P. Sauren, and F. Berendse, 2011: What are the main climate drivers for shrub growth in Northeastern Siberian tundra? *Biogeosciences*, **8(5)**, 1169-1179.

Boero, F., J. Féral, E. Azzurro, V. Cardin, B. Riedel, M. Despalatović, I. Munda, P. Moschella, J. Zaouali, and S. Fonda Umani, 2008: Climate warming and related changes in Mediterranean marine biota. *CIESM Workshop Monographs*, **35**, 5-21.

Bolch, T., A. Kulkarni, A. Kääb, C. Huggel, F. Paul, G. Cogley, H. Frey, J.S. Kargel, K. Fujita, M. Scheel, S. Bajracharya, and M. Stoffel, 2012: The state and fate of Himalayan glaciers. *Science*, **336(6079)**, 310-314.

Bonan, G.B., 2008: Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science*, **320(5882)**, 1444-1449.

Bond-Lamberty, B. and A. Thomson, 2010: Temperature-associated increases in the global soil respiration record. *Nature*, **464(7288)**, 579-582.

Borges, A. and N. Gypens, 2010: Carbonate chemistry in the coastal zone responds more strongly to eutrophication than to ocean acidification. *Limnology and Oceanography*, **55(1)**, 346-353.

Boruff, B.J., J.A. Easoz, S.D. Jones, H.R. Landry, J.D. Mitchem, and S.L. Cutter, 2003: Tornado hazards in the United States. *Climate Research*, **24(2)**, 103-117.

Bouwer, L.M., 2011: Have disaster losses increased due to anthropogenic climate change? *Bulletin of the American Meteorological Society*, **92(1)**, 39-46.

Bouwer, L.M. and W.J.W. Botzen, 2011: How sensitive are US hurricane damages to climate? Comment on a paper by W.D. Nordhaus. *Climate Change Economics*, **02(01)**, 1-7.

Bouwer, L.M., R.P. Crompton, E. Faust, P. Hoppe, and R.A. Pielke Jr., 2007: Confronting disaster losses. *Science*, **318(11)**, 753-753.

Bowman, D., B.P. Murphy, and D.S. Banfai, 2010: Has global environmental change caused monsoon rainforests to expand in the Australian monsoon tropics? *Landscape Ecology*, **25(8)**, 1247-1260.

Bradley, R.S., F.T. Keimig, H.F. Diaz, and D.R. Hardy, 2009: Recent changes in freezing level heights in the tropics with implications for the deglacierization of high mountain regions. *Geophysical Research Letters*, **36(17)**, L17701, doi:10.1029/2009GL037712.

Brander, K.M., 2007: Global fish production and climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **104(50)**, 19709-19714.

Brander, K., 2010: Impacts of climate change on fisheries. *Journal of Marine Systems*, **79(3-4)**, 389-402.

Breetzke, G.D. and E.G. Cohn, 2012: Seasonal assault and neighborhood deprivation in South Africa – some preliminary findings. *Environment and Behavior*, **44(5)**, 641-667.

Brisson, N., P. Gate, D. Gouache, G. Charmet, F. Oury, and F. Huard, 2010: Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. *Field Crops Research*, **119(1)**, 201-212.

Brook, T., 2010: *The Troubled Empire: China in the Yuan and Ming Dynasties.* Belknap Press, Cambridge, MA, USA, 329 pp.

Brooks, H.E. and C.A. Doswell, 2002: Deaths in the 3 May 1999 Oklahoma City tornado from a historical perspective. *Weather and Forecasting*, **17(3)**, 354-361.

Brown, C., R. Meeks, K. Hunu, and W. Yu, 2011: Hydroclimate risk to economic growth in sub-Saharan Africa. *Climatic Change*, **106(4)**, 621-647.

Brown, L.E., D.M. Hannah, and A.M. Milner, 2007: Vulnerability of alpine stream biodiversity to shrinking glaciers and snowpacks. *Global Change Biology*, **13(5)**, 958-966.

Brown, Z.W. and K.R. Arrigo, 2012: Contrasting trends in sea ice and primary production in the Bering Sea and Arctic Ocean. *ICES Journal of Marine Science: Journal Du Conseil*, **69(7)**, 1180-1193.

Brubaker, M., J. Berner, R. Chavan, and J. Warren, 2011: Climate change and health effects in Northwest Alaska. *Global Health Action*, **4**, 8445, doi:10.3402/gha.v4i0.8445.

Bruno, J.F. and E.R. Selig, 2007: Regional decline of coral cover in the Indo-Pacific: timing, extent, and subregional comparisons. *PLoS ONE*, **2(8)**, e711, doi:10.1371/journal.pone.0000711.

Bruno, J.F., E.R. Selig, K.S. Casey, C.A. Page, B.L. Willis, C.D. Harvell, H. Sweatman, and A.M. Melendy, 2007: Thermal stress and coral cover as drivers of coral disease outbreaks. *PLoS Biology*, **5(6)**, 1220-1227.

Bryant, D., L. Burke, J. McManus, and M. Spalding, 1998: *Reefs at Risk: A Map-Based Indicator of Threats to the World's Coral Reefs.* World Resources Institute, Washington, DC, USA, 60 pp.

Buhaug, H. and O.M. Theisen, 2012: On environmental change and armed conflict. In: *Climate Change, Human Security and Violent Conflict* [Scheffran, J. (ed.)]. Springer-Verlag, Berlin Heidelberg, pp. 43-55.

Buhaug, H., H. Hegre, and H. Strand, 2010: *Sensitivity Analysis of Climate Variability and Civil War.* PRIO Paper, Peace Research Institute Oslo (PRIO), Oslo, Norway, 19 pp.

Bullard, R. and B. Wright, 2010: *Race, Place, and Environmental Justice after Hurricane Katrina: Struggles to Reclaim, Rebuild, and Revitalize New Orleans and the Gulf Coast.* Westview Press, Boulder, CO, USA, 312 pp.

Bulygina, O.N., N.N. Korshunova, and V.N. Razuvaev, 2011: Russia. In: *State of the Climate in 2010* [Blunden, J., D.S. Arndt, and M.O. Baringer (eds.)]. Special Supplement to the *Bulletin of the American Meteorological Society*, **92(7 Suppl.)**, S199-S203.

Bunce, M., S. Rosendo, and K. Brown, 2010: Perceptions of climate change, multiple stressors and livelihoods on marginal African coasts. *Environment, Development and Sustainability*, **12(3)**, 407-440.

Burgmer, T., H. Hillebrand, and M. Pfenninger, 2007: Effects of climate-driven temperature changes on the diversity of freshwater macroinvertebrates. *Oecologia*, **151(1)**, 93-103.

Burke, L., K. Reytar, M. Spalding, and A. Perry, 2011: *Reefs at Risk Revisited.* World Resources Institute, Washington, DC, USA, 114 pp.

Burrows, M.T., D.S. Schoeman, L.B. Buckley, P. Moore, E.S. Poloczanska, K.M. Brander, C. Brown, J.F. Bruno, C.M. Duarte, B.S. Halpern, J. Holding, C.V. Kappel, W. Kiessling, M.I. O'Connor, J.M. Pandolfi, C. Parmesan, F.B. Schwing, W.J. Sydeman, and A.J. Richardson, 2011: The pace of shifting climate in marine and terrestrial ecosystems. *Science*, **334(6056)**, 652-655.

Bury, J., B.G. Mark, J. McKenzie, A. French, M. Baraer, K. In Huh, M. Zapata Luyo, and R.J. Gómez López, 2010: Glacier recession and human vulnerability in the Yanamarey Watershed of the Cordillera Blanca, Peru. *Climatic Change*, **105(1-2)**, 179-206.

Butke, P. and S.C. Sheridan, 2010: An analysis of the relationship between weather and aggressive crime in Cleveland, Ohio. *Weather, Climate, and Society*, **2(2)**, 127-139.

Butler, C. and S. Gates, 2012: African range wars: climate, conflict, and property rights. *Journal of Peace Research*, **49(1)**, 23-34.

Butt, N., P.A. De Oliveira, and M.H. Costa, 2011: Evidence that deforestation affects the onset of the rainy season in Rondonia, Brazil. *Journal of Geophysical Research: Atmospheres*, **116**, D11120, doi:10.1029/2010JD015174.

Byg, A. and J. Salick, 2009: Local perspectives on a global phenomenon – climate change in Eastern Tibetan villages. *Global Environmental Change*, **19(2)**, 156-166.

CAFF, 2010: *Arctic Biodiversity Trends 2010 – Selected Indicators of Change.* Arctic Council, Conservation of Arctic Flora and Fauna (CAFF) Working Group, CAFF International Secretariat, Akureyri, Iceland, 121 pp.

Cahill, A.E., M.E. Aiello-Lammens, M.C. Fisher-Reid, X. Hua, C.J. Karanewsky, H.Y. Ryu, G.C. Sbeglia, F. Spagnolo, J.B. Waldron, and O. Warsi, 2013: How does climate change cause extinction? *Proceedings of the Royal Society B*, **280(1750)**, 20121890, doi: 10.1098/rspb.2012.1890.

Cai, W. and T. Cowan, 2006: SAM and regional rainfall in IPCC AR4 models: can anthropogenic forcing account for southwest Western Australian winter rainfall reduction? *Geophysical Research Letters*, **33(24)**, L24708, doi:10.1029/2006GL028037.

Cai, W., T. Cowan, P. Briggs, and M. Raupach, 2009: Rising temperature depletes soil moisture and exacerbates severe drought conditions across southeast Australia. *Geophysical Research Letters*, **36(21)**, L21709, doi:10.1029/2009GL040334.

Callaghan, T.V., F. Bergholm, T.R. Christensen, C. Jonasson, U. Kokfelt, and M. Johansson, 2010: A new climate era in the sub-Arctic. Accelerating climate changes and multiple impacts. *Geophysical Research Letters*, **37(14)**, L14705, doi:10.1029/2009GL042064.

Callaghan, T.V., M. Johansson, R.D. Brown, P.Y. Groisman, N. Labba, V. Radionov, R.G. Barry, R.S. Bradley, S. Blangy, and O.N. Bulygina, 2011: Changing snow cover and its impacts. In: *Snow, Water, Ice and Permafrost in the Arctic (SWIPA).* Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, pp. 1-58.

Callaghan, T.V., C. Jonasson, T. Thierfelder, Z. Yang, H. Hedenås, M. Johansson, U. Molau, R. Van Bogaert, J. Olofsson, D. Jones, S. Bokhorst, G. Phoenix, J. Bjerke, H. Tømmervik, T. Christensen, E. Hanna, E. Koller, and V. Sloan, 2013: Ecosystem change and stability over multiple decades in the Swedish sub-Arctic: complex processes and multiple drivers. *Philosophical Transactions of the Royal Society B*, **368(1624)**, 20120488, doi: 10.1098/rstb.2012.0488.

Callaway, R., A.P. Shinn, S.E. Grenfell, J.E. Bron, G. Burnell, E.J. Cook, M. Crumlish, S. Culloty, K. Davidson, and R.P. Ellis, 2012: Review of climate change impacts on marine aquaculture in the UK and Ireland. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **22(3)**, 389-421.

Cambers, G., 2009: Caribbean beach changes and climate change adaptation. *Aquatic Ecosystem Health and Management*, **12(2)**, 168-176.

Camia, A. and G. Amatulli, 2009: Weather factors and fire danger in the Mediterranean. In: *Earth Observation of Wildland Fires in Mediterranean Ecosystems* [Chuvieco, E. (ed.)]. Springer, Berlin Heidelberg, pp. 71-82.

Cardoso, P.G., D. Raffaelli, and M.A. Pardal, 2008: The impact of extreme weather events on the seagrass *Zostera noltii* and related *Hydrobia ulvae* population. *Marine Pollution Bulletin*, **56(3)**, 483-492.

Carey, M., 2005: Living and dying with glaciers. People's historical vulnerability to avalanches and outburst floods in Peru. *Global and Planetary Change*, **47(2-4)**, 122-134.

Carey, M., 2010: *In the Shadow of Melting Glaciers: Climate Change and Andean Society*. Oxford University Press, Inc., New York, NY, USA, 273 pp.

Carey, M., A. French, and E. O'Brien, 2012a: Unintended effects of technology on climate change adaptation. An historical analysis of water conflicts below Andean glaciers. *Journal of Historical Geography*, **38**, 181-191.

Carey, M., C. Huggel, J. Bury, C. Portocarrero, and W. Haeberli, 2012b: An integrated socio-environmental framework for glacier hazard management and climate change adaptation. Lessons from Lake 513, Cordillera Blanca, Peru. *Climatic Change*, **112(3-4)**, 733-767.

Carilli, J.E., R.D. Norris, B.A. Black, S.M. Walsh, and M. McField, 2009: Local stressors reduce coral resilience to bleaching. *PLoS ONE*, **4(7)**, e6324, doi:10.1371/journal.pone.0006324.

Carpenter, K.E., M. Abrar, G. Aeby, R.B. Aronson, S. Banks, A. Bruckner, A. Chiriboga, J. Cortes, J.C. Delbeek, L. Devantier, G.J. Edgar, A.J. Edwards, D. Fenner, H.M. Guzman, B.W. Hoeksema, G. Hodgson, O. Johan, W.Y. Licuanan, S.R. Livingstone, E.R. Lovell, J.A. Moore, D.O. Obura, D. Ochavillo, B.A. Polidoro, W.F. Precht, M.C. Quibilan, C. Reboton, Z.T. Richards, A.D. Rogers, J. Sanciangco, A. Sheppard, C. Sheppard, J. Smith, S. Stuart, E. Turak, J.E. Veron, C. Wallace, E. Weil, and E. Wood, 2008: One-third of reef-building corals face elevated extinction risk from climate change and local impacts. *Science*, **321(5888)**, 560-563.

Carr, E.R., 2008: Between structure and agency. Livelihoods and adaptation in Ghana's central region. *Global Environmental Change*, **18(4)**, 689-699.

Carreira, P.M., J.M. Marques, A. Pina, A.M. Gomes, P.A.G. Fernandes, and F.M. Santos, 2010: Groundwater assessment at Santiago Island (Cabo Verde): a multidisciplinary approach to a recurring source of water supply. *Water Resources Management*, **24(6)**, 1139-1159.

Carson, C., S. Hajat, B. Armstrong, and P. Wilkinson, 2006: Declining vulnerability to temperature-related mortality in London over the 20th century. *American Journal of Epidemiology*, **164**, 77-84.

Casassa, G.P., B. Pouyaud, and F. Escobar, 2009: Detection of changes in glacial run-off in alpine basins. Examples from North America, the Alps, central Asia and the Andes. *Hydrological Processes*, **23(1)**, 31-41.

Chambers, L.E., 2008: Trends in timing of migration of south-western Australian birds and their relationship to climate. *Emu*, **108(1)**, 1-14.

Chambers, L.E., C.A. Devney, B.C. Congdon, N. Dunlop, E.J. Woehler, and P. Dann, 2011: Observed and predicted effects of climate on Australian seabirds. *Emu*, **111(3)**, 235-251.

Chambers, L.E., P. Dann, B. Cannell, and E.J. Woehler, 2013a: Climate as a driver of phenological change in southern seabirds. *International Journal of Biometeorology* (in press), doi:10.1007/s00484-013-0711-6.

Chambers, L., L. Beaumont, and I. Hudson, 2013b: Continental scale analysis of bird migration timing: influences of climate and life history traits – a generalised mixture model clustering and discriminant approach. *International Journal Biometeorology* (in press), doi:10.1007/s00484-013-0707-2.

Changnon, S.A., 2007: Catastrophic winter storms. An escalating problem. *Climatic Change*, **84(2)**, 131-139.

Changnon, S.A., 2008: Assessment of flood losses in the United States. *Journal of Contemporary Water Research & Education*, **138(1)**, 38-44.

Changnon, S.A., 2009a: Characteristics of severe Atlantic hurricanes in the United States: 1949-2006. *Natural Hazards*, **48(3)**, 329-337.

Changnon, S.A., 2009b: Increasing major hail losses in the U.S. *Climatic Change*, **96(1)**, 161-166.

Chaves, L.F. and C.J.M. Koenraadt, 2010: Climate change and highland malaria. Fresh air for a hot debate. *The Quarterly Review of Biology*, **85(1)**, 27-55.

Chen, C., E. Wang, Q. Yu, and Y. Zhang, 2010: Quantifying the effects of climate trends in the past 43 years (1961-2003) on crop growth and water demand in the North China Plain. *Climatic Change*, **100(3-4)**, 559-578.

Chen, C., C. Lei, A. Deng, C. Qian, W. Hoogmoed, and W. Zhang, 2011: Will higher minimum temperatures increase corn production in Northeast China? An analysis of historical data over 1965-2008. *Agricultural and Forest Meteorology*, **151(12)**, 1580-1588.

Chen, I.C., J.K. Hill, R. Ohlemüller, D.B. Roy, and C.D. Thomas, 2011: Rapid range shifts of species associated with high levels of climate warming. *Science*, **333(6045)**, 1024-1026.

Chessman, B.C., 2009: Climatic changes and 13-year trends in stream macroinvertebrate assemblages in New South Wales, Australia. *Global Change Biology*, **15(11)**, 2791-2802.

Cheung, W.W., R. Watson, and D. Pauly, 2013: Signature of ocean warming in global fisheries catch. *Nature*, **497(7449)**, 365-368.

Chinn, T.B., B. Fitzharris, A. Willsman, and M.J. Salinger, 2012: Annual ice volume changes (1976-2008) for the New Zealand Southern Alps. *Global and Planetary Change*, **92(7)**, 105-118.

Chongvilaivan, A., 2012: *Thailand's 2011 Flooding: Its Impact on Direct Exports and Global Supply Chains.* ARTNeT Working Paper Series, No 113, ARTNeT Secretariat, United Nations Economic and Social Commission for Asia and the Pacific (ESCAP), Trade and Investment Division, Bangkok, Thailand, 33 pp.

Christidis, N., G.C. Donaldson, and P.A. Stott, 2010: Causes for the recent changes in cold- and heat-related mortality in England and Wales. *Climatic Change*, **102(3-4)**, 539-553.

Christidis, N., P.A. Stott, and S.J. Brown, 2011: The role of human activity in the recent warming of extremely warm daytime temperatures. *Journal of Climate*, **24(7)**, 1922-1930.

Cinner, J., T. McClanahan, N. Graham, T. Daw, J. Maina, S. Stead, A. Wamukota, K. Brown, and Ö. Bodin, 2012: Vulnerability of coastal communities to key impacts of climate change on coral reef fisheries. *Global Environmental Change*, **22(1)**, 12-20.

Clarke, H., C. Lucas, and P. Smith, 2012: Changes in Australian fire weather between 1973 and 2010. *International Journal of Climatology*, **33(4)**, 931-944.

Cogley, J.G., 2012: Climate science: Himalayan glaciers in the balance. *Nature*, **488(7412)**, 7412-7469.

Cole, J.H. and A.M. Gramajo, 2009: Homicide rates in a cross-section of countries: evidence and interpretations. *Population and Development Review*, **35(4)**, 749-776.

Cole, J., Y. Prairie, N. Caraco, W. McDowell, L. Tranvik, R. Striegl, C. Duarte, P. Kortelainen, J. Downing, and J. Middelburg, 2007: Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget. *Ecosystems*, **10(1)**, 172-185.

Coles, S.L. and B.M. Riegl, 2012: Thermal tolerances of reef corals in the Gulf: a review of the potential for increasing coral survival and adaptation to climate change through assisted translocation. *Marine Pollution Bulletin*, **72(2)**, 323-332.

Collie, J.S., K. Richardson, and J.H. Steele, 2004: Regime shifts: can ecological theory illuminate the mechanisms? *Progress in Oceanography*, **60(2)**, 281-302.

Collins, D.N., 2006: Climatic variation and runoff in mountain basins with differing proportions of glacier cover. *Nordic Hydrology*, **37(4-5)**, 315-326.

Comeaux, R.S., M.A. Allison, and T.S. Bianchi, 2012: Mangrove expansion in the Gulf of Mexico with climate change: implications for wetland health and resistance to rising sea levels. *Estuarine, Coastal and Shelf Science*, **96**, 81-95.

Confalonieri, U., B. Menne, R. Akhtar, K.L. Ebi, M. Hauengue, R.S. Kovats, B. Revich, and A. Woodward, 2007: Human health. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., Canziani, O.F., J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 391-431.

Conway, D. and G. Mahé, 2009: River flow modelling in two large river basins with non-stationary behaviour: the Paraná and the Niger. *Hydrological Processes*, **23(22)**, 3186-3192.

Cook, B.I., E.M. Wolkovich, and C. Parmesan, 2012a: Divergent responses to spring and winter warming drive community level flowering trends. *Proceedings of the National Academy of Sciences of the United States of America*, **109(23)**, 9000-9005.

Cook, B., E. Wolkovich, T.J. Davies, T. Ault, J. Betancourt, J. Allen, K. Bolmgren, E. Cleland, T. Crimmins, N.B. Kraft, L. Lancaster, S. Mazer, G. McCabe, B. McGill, C. Parmesan, S. Pau, J. Regetz, N. Salamin, M. Schwartz, and S. Travers, 2012b: Sensitivity of spring phenology to warming across temporal and spatial climate gradients in two independent databases. *Ecosystems*, **15(8)**, 1283-1294.

Cooley, S.R. and S.C. Doney, 2009: Anticipating ocean acidification's economic consequences for commercial fisheries. *Environmental Research Letters*, **4(2)**, 024007, doi:10.1088/1748-9326/4/2/024007.

Cooper, T.F., G. De'ath, K.E. Fabricius, and J.M. Lough, 2008: Declining coral calcification in massive *Porites* in two nearshore regions of the northern Great Barrier Reef. *Global Change Biology*, **14(3)**, 529-538.

Cosgrave, J., C. Goncalves, D. Martyris, R. Polastro, and M. Sikumba-Dils, 2007: *Inter-Agency Real-Time Evaluation of the Response to the February 2007 Floods and Cyclone in Mozambique.* Inter-Agency Humanitarian Standing Committee, 91 pp., www.unicef.org/evaldatabase/files/MOZ_RTE_2007_Floodsandcyclone.pdf.

Costa, L., K. Thonicke, B. Poulter, and F. Badeck, 2011: Sensitivity of Portuguese forest fires to climatic, human, and landscape variables: subnational differences between fire drivers in extreme fire years and decadal averages. *Regional Environmental Change*, **11(3)**, 543-551.

Costard, F., E. Gautier, D. Brunstein, J. Hammadi, A. Fedorov, D. Yang, and L. Dupeyrat, 2007: Impact of the global warming on the fluvial thermal erosion over the Lena River in Central Siberia. *Geophysical Research Letters*, **34(14)**, L14501, doi:10.1029/2007GL030212.

Coumou, D., A. Robinson, and S. Rahmstorf, 2013: Global increase in record-breaking monthly-mean temperatures. *Climatic Change*, **118(3-4)**, 771-782.

Courbage, C., M. Orie, and W.R. Stahel, 2012: 2011 Thai floods and insurance. In: *Extreme Events and Insurance: 2011 Annus Horribilis* [Courbage, C. and W.R. Stahel (eds.)]. The Geneva Reports – Risk and Insurance Research No. 5, The Geneva Association, Geneva, Switzerland, pp. 121-132.

Crate, S.A., 2013: *Climate Change and Human Mobility in Indigenous Communities of the Russian North.* Project Report, Brookings-LSE Project on Internal Displacement, Brookings Institution, Washington, DC, USA, 45 pp.

Crompton, R.P., K.J. McAneney, K. Chen, R.A. Pielke Jr., and K. Haynes, 2010: Influence of location, population, and climate on building damage and fatalities due to Australian Bushfire: 1925-2009. *Weather, Climate, and Society*, **2(4)**, 300-310.

Crouch, J., R.R. Heim Jr., P. Hughes, and C. Fenimore, 2013: United States. In: *State of the Climate in 2012* [Blunden, J. and D.S. Arndt (eds.)]. Special Supplement to the *Bulletin of the American Meteorological Society*, **94(8 Suppl.)**, S149-S152.

Croxall, J., P. Trathan, and E. Murphy, 2002: Environmental change and Antarctic seabird populations. *Science*, **297(5586)**, 1510-1514.

Cruikshank, J., 2001: Glaciers and climate change. Perspectives from oral tradition. *Arctic*, **54**, 377-393.

Crutchfield, S., 2013: *U.S. Drought 2012: Farm and Food Impacts.* United States Department of Agriculture (USDA) Economic Research Service, www.ers.usda.gov/topics/in-the-news/us-drought-2012-farm-and-food-impacts.aspx#.UxiOWfldXTo.

Cullen-Unsworth, L.C., R. Hill, J.R.A. Butler, and M. Wallace, 2012: A research process for integrating indigenous and scientific knowledge in cultural landscapes: principles and determinants of success in the wet tropics world heritage area, Australia. *The Geographical Journal*, **178(4)**, 351-365.

Curry, J., 2011: Nullifying the climate null hypothesis. *Wiley Interdisciplinary Reviews: Climate Change*, **2**, 919-924.

Cutter, S., B. Osman-Elasha, J. Campbell, S.M. Cheong, S. McCormick, R. Pulwarty, S. Supratid, and G. Ziervogel, 2012: Managing the risks from climate extremes at the local level. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 291-338.

D'Amato, G., L. Cecchi, S. Bonini, C. Nunes, I. Annesi-Maesano, H. Behrendt, G. Liccardi, T. Popov, and P. Van Cauwenberge, 2007: Allergenic pollen and pollen allergy in Europe. *Allergy*, **62(9)**, 976-990.

Daanen, R.P., G. Grosse, M.M. Darrow, T.D. Hamilton, and B.M. Jones, 2012: Rapid movement of frozen debris-lobes: implications for permafrost degradation and slope instability in the south-central Brooks Range, Alaska. *Natural Hazards and Earth System Sciences*, **12(5)**, 1521-1537.

Dai, A., 2011: Drought under global warming: a review. *Wiley Interdisciplinary Reviews: Climate Change*, **2(1)**, 45-65.

Dai, A., K.E. Trenberth, and J.D. Milliman, 2009: Changes in continental freshwater discharge from 1948 to 2004. *Journal of Climate*, **22(10)**, 2773-2792.

Dalton, S.J., S. Godwin, S.D.A. Smith, and L. Pereg, 2010: Australian subtropical white syndrome: a transmissible, temperature-dependent coral disease. *Marine and Freshwater Research*, **61(3)**, 342-350.

Dash, S. and T. Kjellström, 2011: Workplace heat stress in the context of rising temperature in India. *Current Science*, **101(4)**, 496-503.

Davidson, E.A., A.C. de Araújo, P. Artaxo, J.K. Balch, I.F. Brown, M.M. Bustamante, M.T. Coe, R.S. DeFries, M. Keller, and M. Longo, 2012: The Amazon basin in transition. *Nature*, **481(7381)**, 321-328.

De Moel, H., G.M. Ganssen, F.J.C. Peeters, S.J.A. Jung, D. Kroon, G.J.A. Brummer, and R.E. Zeebe, 2009: Planktic foraminiferal shell thinning in the Arabian Sea due to anthropogenic ocean acidification? *Biogeosciences*, **6(9)**, 1917-1925.

De'ath, G., J.M. Lough, and K.E. Fabricius, 2009: Declining coral calcification on the Great Barrier Reef. *Science*, **323(5910)**, 116-119.

De'ath, G., K. Fabricius, H. Sweatman, and M. Puotinen, 2012: The 27 year decline of coral cover on the Great Barrier Reef and its causes. *Proceedings of the National Academy of Sciences of the United States of America*, **109(44)**, 17995-17999.

Delaloye, R., C. Lambiel, and I. Gärtner-Roer, 2010: Overview of rock glacier kinematics research in the Swiss Alps. Seasonal rhythm, interannual variations and trends over several decades. *Geographica Helvetica*, **65(2)**, 135-145.

Dell, M., B.F. Jones, and B.A. Olken, 2009: Temperature and income: reconciling new cross-sectional and panel estimates. *American Economic Review*, **99(2)**, 198-204.

Dell, M., B.F. Jones, and B.A. Olken, 2012: Temperature shocks and economic growth: evidence from the last half century. *American Economic Journal: Macroeconomics*, **4(3)**, 66-95.

Delpla, I., A.V. Jung, E. Baures, M. Clement, and O. Thomas, 2009: Impacts of climate change on surface water quality in relation to drinking water production. *Environment International*, **35(8)**, 1225-1233.

Deschênes, O. and M. Greenstone, 2007: The economic impacts of climate change: evidence from agricultural output and random fluctuations in weather. *The American Economic Review*, **97(1)**, 354-385.

Deschênes, O. and M. Greenstone, 2011: Climate change, mortality, and adaptation: evidence from annual fluctuations in weather in the US. *American Economic Journal: Applied Economics*, **3(4)**, 152-185.

Descy, J.P. and H. Sarmento, 2008: Microorganisms of the East African Great Lakes and their response to environmental changes. *Freshwater Reviews*, **1**, 59-73.

Devictor, V., R. Julliard, D. Couvet, and F. Jiguet, 2008: Birds are tracking climate warming, but not fast enough. *Proceedings of the Royal Society B*, **275**, 2743-2748.

Devictor, V., C. Van Swaay, T. Brereton, L. Brotons, D. Chamberlain, J. Heliola, S. Herrando, R. Julliard, M. Kuussaari, A. Lindström, J. Reif, D.B. Roy, O. Schweiger, J. Settele, C. Stefanescu, A. Van Strien, C. Van Turnhout, Z. Vermouzek, M. Wallis De Vries, I. Wynhoff, and F. Jiguet, 2012: Differences in the climatic debts of birds and butterflies at a continental scale. *Nature Climate Change*, **2(2)**, 121-124.

deYoung, B. and A. Jarre, 2009: Regime shifts: methods of analysis. In: *Encyclopedia of Ocean Sciences* [Steele, J.H., K.K. Turekian, and S.A. Thorpe (eds.)]. 2nd edn., Academic Press, Oxford, UK, pp. 717-721.

deYoung, B., M. Barange, G. Beaugrand, R. Harris, R.I. Perry, M. Scheffer, and F. Werner, 2008: Regime shifts in marine ecosystems: detection, prediction and management. *Trends in Ecology & Evolution*, **23(7)**, 402-409.

Di Baldassarre, G., A. Montanari, H. Lins, D. Koutsoyiannis, L. Brandimarte, and G. Blöschl, 2010: Flood fatalities in Africa: from diagnosis to mitigation. *Geophysical Research Letters*, **37(22)**, L22402, doi:10.1029/2010GL045467.

Diaz, R.J. and R. Rosenberg, 2008: Spreading dead zones and consequences for marine ecosystems. *Science*, **321(5891)**, 926-929.

Diemberger, H., K. Hastrup, S. Schaffer, C.F. Kennel, D. Sneath, M. Bravo, H.F. Graf, J. Hobbs, J. Davis, and M.L. Nodari, 2012: Communicating climate knowledge: proxies, processes, politics. Commentaries. *Current Anthropology*, **53(2)**, 226-244.

Dietz, A.J., R. Ruben, and A. Verhagen (eds.), 2004: *The Impact of Climate Change on Drylands: With a Focus on West Africa*. Environment & Policy, Vol. 39, Kluwer Academic Publishers, Dordrecht, Netherlands, 465 pp.

Díez, I., N. Muguerza, A. Santolaria, U. Ganzedo, and J. Gorostiaga, 2012: Seaweed assemblage changes in the eastern Cantabrian Sea and their potential relationship to climate change. *Estuarine, Coastal and Shelf Science*, **99**, 108-120.

d'Orgeval, T. and J. Polcher, 2008: Impacts of precipitation events and land-use changes on West African river discharges during the years 1951-2000. *Climate Dynamics*, **31(2-3)**, 249-262.

Douglas, I., K. Alam, M.A. Maghenda, Y. Mcdonnell, L. McLean, and J. Campbell, 2008: Unjust waters. Climate change, flooding and the urban poor in Africa. *Environment and Urbanization*, **20(1)**, 187-205.

Doyle, M.E. and V.R. Barros, 2011: Attribution of the river flow growth in the Plata basin. *International Journal of Climatology*, **31(15)**, 2234-2248.

Duarte, C.M., S. Agustí, P. Wassmann, J.M. Arrieta, M. Alcaraz, A. Coello, N. Marbà, I.E. Hendriks, J. Holding, and I. García-Zarandona, 2012a: Tipping elements in the Arctic marine ecosystem. *AMBIO*, **41(1)**, 44-55.

Duarte, C.M., T.M. Lenton, P. Wadhams, and P. Wassmann, 2012b: Abrupt climate change in the Arctic. *Nature Climate Change*, **2(2)**, 60-62.

Duarte, C.M., I. Hendriks, T. Moore, Y. Olsen, A. Steckenbauer, L. Ramajo, J. Carstensen, J. Trotter, and M. McCulloch, 2013: Is ocean acidification an open-ocean syndrome? Understanding anthropogenic impacts on marine pH. *Estuaries and Coasts*, **36(2)**, 221-236.

Dunne, J.P., R.J. Stouffer, and J.G. John, 2013: Reductions in labour capacity from heat stress under climate warming. *Nature Climate Change*, **3**, 563-566

Durance, I. and S.J. Ormerod, 2007: Climate change effects on upland stream macroinvertebrates over a 25-year period. *Global Change Biology*, **13(5)**, 942-957.

Durand, Y., G. Giraud, M. Laternser, P. Etchevers, L. Mérindol, and B. Lesaffre, 2009: Reanalysis of 47 years of climate in the French Alps (1958-2005): climatology and trends for snow cover. *Journal of Applied Meteorology and Climatology*, **48(12)**, 2487-2512.

Eakin, C.M., J.A. Morgan, S.F. Heron, T.B. Smith, G. Liu, L. Alvarez-Filip, B. Baca, E. Bartels, C. Bastidas, C. Bouchon, M. Brandt, A.W. Bruckner, L. Bunkley-Williams, A. Cameron, B.D. Causey, M. Chiappone, T.R.L. Christensen, M.J.C. Crabbe, O. Day, E. de la Guardia, G. Diaz-Pulido, D. DiResta, D.L. Gil-Agudelo, D.S. Gilliam, R.N. Ginsburg, S. Gore, H.M. Guzman, J.C. Hendee, E.A. Hernandez-Delgado, E. Husain, C.F.G. Jeffrey, R.J. Jones, E. Jordan-Dahlgren, L.S. Kaufman, D.I. Kline, P.A. Kramer, J.C. Lang, D. Lirman, J. Mallela, C. Manfrino, J. Marechal, K. Marks, J. Mihaly, W.J. Miller, E.M. Mueller, E.M. Muller, C.A. Orozco Toro, H.A. Oxenford, D. Ponce-Taylor, N. Quinn, K.B. Ritchie, S. Rodriguez, A. Rodriguez Ramirez, S. Romano, J.F. Samhouri, J.A. Sanchez, G.P. Schmahl, B.V. Shank, W.J. Skirving, S.C.C. Steiner, E. Villamizar, S.M. Walsh, C. Walter, E. Weil, E.H. Williams, K.W. Roberson, and Y. Yusuf, 2010: Caribbean corals in crisis: record thermal stress, bleaching, and mortality in 2005. *PLoS ONE*, **5(11)**, e13969, doi:10.1371/journal.pone.0013969.

Ebinger, J.O. and W. Vegara, 2011: *Climate Impacts on Energy Systems: Key Issues for Energy Sector Adaptation.* World Bank, Energy Sector Management Assistance Program (ESMAP), The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 178 pp.

Eckert, N., C.J. Keylock, H. Castebrunet, A. Lavigne, and M. Naaim, 2013: Temporal trends in avalanche activity in the French Alps and subregions: from occurrences and runout altitudes to unsteady return periods. *Journal of Glaciology*, **59(213)**, 93-114.

Edwards, M. and A.J. Richardson, 2004: Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature*, **430(7002)**, 881-884.

Eijgelaar, E., C. Thaper, and P. Peeters, 2010: Antarctic cruise tourism: the paradoxes of ambassadorship, 'last chance tourism' and greenhouse gas emissions. *Journal of Sustainable Tourism*, **18(3)**, 337-354.

Eira, I.M.G., 2012: *Muohttaga Jávohis Giella: Sámi Árbevirolaš Máhttu Muohttaga Birra Dálkkádatrievdanáiggis (The Silent Language of Snow: Sámi Traditional Knowledge of Snow in Times of Climate Change).* Ph.D. Dissertation, University of Tromsø, Tromsø, Norway.

Ekau, W., H. Auel, H.O. Pörtner, W. Gilbert, and D. Gilbert, 2010: Impacts of hypoxia on the structure and processes in pelagic communities (zooplankton, macro-invertebrates and fish). *Biogeosciences*, **7(5)**, 1669-1699.

Eliason, E.J., T.D. Clark, M.J. Hague, L.M. Hanson, Z.S. Gallagher, K.M. Jeffries, M.K. Gale, D.A. Patterson, S.G. Hinch, and A.P. Farrell, 2011: Differences in thermal tolerance among sockeye salmon populations. *Science*, **332(6025)**, 109-112.

Elliott, J.R. and J. Pais, 2006: Race, class, and Hurricane Katrina: social differences in human responses to disaster. *Social Science Research*, **35(2)**, 295-321.

Elmendorf, S.C., G.H.R. Henry, R.D. Hollister, R.G. Björk, N. Boulanger-Lapointe, E.J. Cooper, J.H.C. Cornelissen, T.A. Day, E. Dorrepaal, T.G. Elumeeva, M. Gill, W.A. Gould, J. Harte, D.S. Hik, A. Hofgaard, D.R. Johnson, J.F. Johnstone, I.S. Jónsdóttir, J.C. Jorgenson, K. Klanderud, J.A. Klein, S. Koh, G. Kudo, M. Lara, E. Lévesque, B. Magnússon, J.L. May, J.A. Mercado-Díaz, A. Michelsen, U. Molau, I.H. Myers-Smith, S.F. Oberbauer, V.G. Onipchenko, C. Rixen, N.M. Schmidt, G.R. Shaver, M.J. Spasojevic, T.E. Thórhallsdóttir, A. Tolvanen, T. Troxler, C.E. Tweedie, S. Villareal, C.H. Wahren, X. Walker, P.J. Webber, J.M. Welker, and S. Wipf, 2012: Plot-scale evidence of tundra vegetation change and links to recent summer warming. *Nature Climate Change*, **2(6)**, 453-457.

Espinoza, J.C., J. Ronchail, F. Frappart, W. Lavado, W. Santini, and J.L. Guyot, 2013: The major floods in the Amazonas River and Tributaries (Western Amazon Basin) during the 1970-2012 Period: a focus on the 2012 Flood. *Journal of Hydrometeorology*, **14(3)**, 1000-1008.

Etter, A., C. McAlpine, S. Phinn, D. Pullar, and H. Possingham, 2006: Unplanned land clearing of Colombian rainforests: spreading like disease? *Landscape and Urban Planning*, **77(3)**, 240-254.

Evans, S.G. and J.J. Clague, 1994: Recent climatic change and catastrophic geomorphic processes in mountain environments. *Geomorphology*, **10(1-4)**, 107-128.

Fajnzylber, P., D. Lederman, and N. Loayza, 2002: What causes violent crime? *European Economic Review*, **46(7)**, 1323-1357.

FAOSTAT, 2013: *Food and Agriculture Organization of the United Nations Database on Agriculture.* FAO, Rome, Italy, faostat.fao.org/site/291/default.aspx.

Farbotko, C., 2010: 'The global warming clock is ticking so see these places while you can': voyeuristic tourism and model environmental citizens on Tuvalu's disappearing islands. *Singapore Journal of Tropical Geography*, **31(2)**, 224-238.

Fauria, M.M. and E. Johnson, 2008: Climate and wildfires in the North American boreal forest. *Philosophical Transactions of the Royal Society B*, **363(1501)**, 2315-2327.

Feely, R.A., S.R. Alin, J. Newton, C.L. Sabine, M. Warner, A. Devol, C. Krembs, and C. Maloy, 2010: The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary. *Estuarine, Coastal and Shelf Science*, **88(4)**, 442-449.

Feng, S. and M. Oppenheimer, 2012: Applying statistical models to the climate–migration relationship. *Proceedings of the National Academy of Sciences of the United States of America*, **109(43)**, E2915, doi:10.1073/pnas.1212226109.

Feng, S., M. Oppenheimer, and W. Schlenker, 2012: *Climate Change, Crop Yields, and Internal Migration in the United States.* NBER Working Paper 17734, National Bureau of Economic Research (NBER), Cambridge, MA, USA, 43 pp.

Fernández, C., 2011: The retreat of large brown seaweeds on the north coast of Spain: the case of *Saccorhiza polyschides*. *European Journal of Phycology*, **46(4)**, 352-360.

Field, S., 1992: The effect of temperature on crime. *British Journal of Criminology*, **32(3)**, 340-351.

Fischer, L., R.S. Purves, C. Huggel, J. Noetzli, and W. Haeberli, 2012: On the influence of geological, topographic and glaciological factors on slope instabilities. Analyses of recent Alpine rock avalanches. *Natural Hazards and Earth System Sciences*, **12**, 241-254.

Fischlin, A., G.F. Midgley, J.T. Price, R. Leemans, B. Gopal, C. Turley, M.D.A. Rounsevell, O.P. Dube, J. Tarazona, and A.A. Velichko, 2007: Ecosystems, their properties, goods, and services. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 211-272.

Fishman, J., J.K. Creilson, P.A. Parker, E.A. Ainsworth, G.G. Vining, J. Szarka, L. Booker, and X. Xu, 2010: An investigation of widespread ozone damage to the soybean crop in the upper Midwest determined from ground-based and satellite measurements. *Atmospheric Environment*, **44(18)**, 2248-2256.

Foden, W., G.F. Midgley, G. Hughes, W.J. Bond, W. Thuiller, M.T. Hoffmann, P. Kaleme, L.G. Underhill, A. Rebelo, and L. Hannah, 2007: A changing climate is eroding the geographical range of the Namib Desert tree *Aloe* through population declines and dispersal lags. *Diversity and Distributions*, **13**, 645-653.

Foley, C., 2007: *Mozambique: A Case Study in the Role of the Affected State in Humanitarian Action.* Humanitarian Policy Working Paper, Overseas Development Institute (ODI), London, UK, 32 pp.

Forbes, D.L. (ed.), 2011: *State of the Arctic Coast 2010 – Scientific Review and Outlook*. International Arctic Science Committee (IASC), Land-Ocean Interactions in the Coastal Zone (LOICZ), Arctic Monitoring and Assessment Programme (AMAP), International Permafrost Association (IPA), Helmholtz-Zentrum, Geesthacht, Germany, 168 pp.

Forcada, J., P.N. Trathan, and E.J. Murphy, 2008: Life history buffering in Antarctic mammals and birds against changing patterns of climate and environmental variation. *Global Change Biology*, **14(11)**, 2473-2488.

Ford, J.D., 2009a: Vulnerability of Inuit food systems to food insecurity as a consequence of climate change: a case study from Igloolik, Nunavut. *Regional Environmental Change*, **9(2)**, 83-100.

Ford, J.D., 2009b: Dangerous climate change and the importance of adaptation for the Arctic's Inuit population. *Environmental Research Letters*, **4(2)**, 024006, doi:10.1088/1748-9326/4/2/024006.

Ford, J.D., W.A. Gough, G.J. Laidler, J. MacDonald, C. Irngaut, and K. Qrunnut, 2009: Sea ice, climate change, and community vulnerability in northern Foxe Basin, Canada. *Climate Research*, **38**, 137-154.

Ford, J.D., W. Vanderbilt, and L. Berrang-Ford, 2011: Authorship in IPCC AR5 and its implications for content. Climate change and indigenous populations in WGII. *Climatic Change*, **113(2)**, 201-213.

Ford, M., 2012: Shoreline changes on an urban atoll in the central Pacific Ocean. Majuro Atoll, Marshall Islands. *Journal of Coastal Research*, **28(1)**, 11-22.

Forkel, M., K. Thonicke, C. Beer, W. Cramer, S. Bartalev, and C. Schmullius, 2012: Extreme fire events are related to previous-year surface moisture conditions in permafrost-underlain larch forests of Siberia. *Environmental Research Letters*, **7(4)**, 044021, doi:10.1088/1748-9326/7/4/044021.

Fouillet, A., G. Rey, F. Laurent, G. Pavillon, S. Bellec, C. Guihenneuc-Jouyaux, J. Clavel, E. Jougla, and D. Hémon, 2006: Excess mortality related to the August 2003 heat wave in France. *Occupational and Environmental Health*, **80**, 16-24.

Fouillet, A., G. Rey, V. Wagner, K. Laaidi, P. Empereur-Bissonnet, A. le Tertre, P. Frayssinet, P. Bessemoulin, F. Laurent, P. Crouy-Chanel, E. Jougla, and D. Hémon, 2008: Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave. *International Journal of Epidemiology*, **37(2)**, 309-317.

Fowbert, J.A. and R.I.L. Smith, 1994: Rapid population increases in native vascular plants in the Argentine Islands, Antarctic Peninsula. *Arctic and Alpine Research*, **26**, 290-296.

Franco, G. and A.H. Sanstad, 2008: Climate change and electricity demand in California. *Climatic Change*, **87(1)**, 139-151.

Gamble, D.W., D. Campbell, T.L. Allen, D. Barker, S. Curtis, D. McGregor, and J. Popke, 2010: Climate change, drought, and Jamaican agriculture: local knowledge and the climate record. *Annals of the Association of American Geographers*, **100(4)**, 880-893.

Gamble, J.L. and J.J. Hess, 2012: Temperature and violent crime in Dallas, Texas: relationships and implications of climate change. *Western Journal of Emergency Medicine*, **13(3)**, 239-246.

García-Mozo, H., C. Galán, P. Alcázar, C. de la Guardia, D. Nieto-Lugilde, M. Recio, P. Hidalgo, F. Gónzalez-Minero, L. Ruiz, and E. Domínguez-Vilches, 2010: Trends in grass pollen season in southern Spain. *Aerobiologia*, **26(2)**, 157-169.

Gardelle, J., Y. Arnaud, and E. Berthier, 2011: Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009. *Global and Planetary Change*, **75(1-2)**, 47-55.

Gardelle, J., E. Berthier, and Y. Arnaud, 2012: Slight mass gain of Karakoram glaciers in the early twenty-first century. *Nature Geoscience*, **5(5)**, 322-325.

Gardner, A.S., G. Moholdt, B. Wouters, G.J. Wolken, D.O. Burgess, M.J. Sharp, J.G. Cogley, C. Braun, and C. Labine, 2011: Sharply increased mass loss from glaciers and ice caps in the Canadian Arctic Archipelago. *Nature*, **473(7347)**, 357-360.

Gardner, A.S., G. Moholdt, J.G. Cogley, A.A. Arendt, B. Wouters, J. Wahr, W.T. Pfeffer, G. Kaser, S.R.M. Ligtenberg, T. Bolch, R. Hock, E. Berthier, M.J. Sharp, J.O. Hagen, M. van den Broeke, F. Paul, and V. Radic, 2013: A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. *Science*, **340(6134)**, 852-857.

Gardner, T.A., I.M. Côté, J.A. Gill, A. Grant, and A.R. Watkinson, 2003: Long-term region-wide declines in Caribbean corals. *Science*, **301(5635)**, 958-960.

Garrabou, J., R. Coma, N. Bensoussan, M. Bally, P. Chevaldonné, M. Cigliano, D. Diaz, J.G. Harmelin, M.C. Gambi, D.K. Kersting, J.B. Ledoux, C. Lejesune, C. Linares, C. Marschal, T. Pérez, M. Ribes, J.C. Romano, E. Serrano, N. Teixido, O. Torrents, M. Zabala, F. Zuberer, and C. Cerrano, 2009: Mass mortality in Northwestern Mediterranean rocky benthic communities: effects of the 2003 heat wave. *Global Change Biology*, **15(5)**, 1090-1103.

Gaston, A.J., H.G. Gilchrist, M.L. Mallory, and P.A. Smith, 2009: Changes in seasonal events, peak food availability, and consequent breeding adjustment in a marine bird: a case of progressive mismatching. *The Condor*, **111(1)**, 111-119.

Gaydon, R.S., H.G. Beecher, R. Reinke, S. Crimp, and S.M. Howden, 2010: Rice. In: *Adapting Agriculture to Climate Change. Preparing Australian Agriculture, Forestry and Fisheries for the Future* [Stokes, C. and S. Howden (eds.)]. CSIRO Publishing, Collingwood, Australia, pp. 67-83.

Gehrig-Fasel, J., A. Guisan, and N.E. Zimmermann, 2007: Tree line shifts in the Swiss Alps: climate change or land abandonment? *Journal of Vegetation Science*, **18(4)**, 571-582.

Georgakakos, A., P. Fleming, M. Dettinger, C. Peters-Lidgard, T.C. Richmond, K. Reckhow, K. White, and D. Yates, 2013: Chapter 3: Water resources. In: *National Climate Assessment*. U.S. Global Change Research Program, Draft for public review, pp. 107-164, ncadac.globalchange.gov/.

Gething, P.W., D.L. Smith, A.P. Patil, A.J. Tatem, R.W. Snow, and S.I. Hay, 2010: Climate change and the global malaria recession. *Nature*, **465(7296)**, 342-345.

Global Fire Monitoring Center, 2010: Preliminary assessment of the fire situation in western Russia. *International Forest Fire News*, **40**, 20-42, www.fire.uni-freiburg.de/iffn/iffn_40/03-Russia-I.pdf.

Giannini, A., M. Biasutti, and M.M. Verstraete, 2008: A climate model-based review of drought in the Sahel. Desertification, the re-greening and climate change. *Global and Planetary Change*, **64(3-4)**, 119-128.

Gillett, N.P., A.J. Weaver, F.W. Zwiers, and M.D. Flannigan, 2004: Detecting the effect of climate change on Canadian forest fires. *Geophysical Research Letters*, **31(18)**, L18211, doi:10.1029/2004GL020876.

Gilman, E.L., J. Ellison, N.C. Duke, and C. Field, 2008: Threats to mangroves from climate change and adaptation options: a review. *Aquatic Botany*, **89(2)**, 237-250.

Girardin, M.P. and M. Mudelsee, 2008: Past and future changes in Canadian boreal wildfire activity. *Ecological Applications*, **18(2)**, 391-406.

Girardin, M.P., A.A. Ali, C. Carcaillet, S. Gauthier, C. Hély, H. Le Goff, A. Terrier, and Y. Bergeron, 2013: Fire in managed forests of eastern Canada: risks and options. Special Issue: "The Mega Fire Reality" of *Forest Ecology and Management*, **294**, 238-249.

Giri, C., E. Ochieng, L.L. Tieszen, Z. Zhu, A. Singh, T. Loveland, J. Masek, and N. Duke, 2011: Status and distribution of mangrove forests of the world using earth observation satellite data. *Global Ecology and Biogeography*, **20(1)**, 154-159.

Goetz, S., M. Mack, K. Gurney, J. Randerson, and R. Houghton, 2007: Ecosystem responses to recent climate change and fire disturbance at northern high latitudes: observations and model results contrasting northern Eurasia and North America. *Environmental Research Letters*, **2(4)**, 045031, doi:10.1088/1748-9326/2/4/045031.

Goldblum, D. and L.S. Rigg, 2010: The deciduous forest–boreal forest ecotone. *Geography Compass*, **4(7)**, 701-717.

Gonzalez, P., C.J. Tucker, and H. Sy, 2012: Tree density and species decline in the African Sahel attributable to climate. *Journal of Arid Environments*, **78**, 55-64.

Goodman, J., J. Maschinski, P. Hughes, J. Mcauliffe, J. Roncal, D. Powell, and L.O. Sternberg, 2012: Differential response to soil salinity in endangered key tree cactus. Implications for survival in a changing climate. *PLoS ONE*, **7(3)**, e32528, doi:10.1371/journal.pone.0032528.

Gooseff, M.N., A. Balser, W.B. Bowden, and J.B. Jones, 2009: Effects of hillslope thermokarst in Northern Alaska. *EOS, Transactions of the American Geophysical Union*, **90(4)**, 29-30, doi:10.1029/2009EO040001.

Gray, J.S., H. Dautel, A. Estrada-Peña, O. Kahl, and E. Lindgren, 2009: Effects of climate change on ticks and tick-borne diseases in Europe. *Interdisciplinary Perspectives on Infectious Diseases*, **2009**, 593232, doi:10.1155/2009/593232.

Green, D. and G. Raygorodetsky, 2010: Indigenous knowledge of a changing climate. *Climatic Change*, **100(2)**, 239-242.

Green, K., 2010: Alpine taxa exhibit differing responses to climate warming in the Snowy Mountains of Australia. *Journal of Mountain Science*, **7**, 167-175.

Greene, A.M., A. Giannini, and S.E. Zebiak, 2009: Drought return times in the Sahel: a question of attribution. *Geophysical Research Letters*, **36(12)**, L12701, doi:10.1029/2009GL038868.

Gregory, P.J. and B. Marshall, 2012: Attribution of climate change: a methodology to estimate the potential contribution to increases in potato yield in Scotland since 1960. *Global Change Biology*, **18(4)**, 1372-1388.

Grémillet, D. and T. Boulinier, 2009: Spatial ecology and conservation of seabirds facing global climate change. A review. *Marine Ecology Progress Series*, **391**, 121-137.

Groisman, P.Y., B.G. Sherstyukov, V.N. Razuvaev, R.W. Knight, J.G. Enloe, N.S. Stroumentova, P.H. Whitfield, E. Førland, I. Hannsen-Bauer, H. Tuomenvirta, H. Aleksandersson, A.V. Mescherskaya, and T.R. Karl, 2007: Potential forest fire danger over Northern Eurasia: changes during the 20th century. *Global and Planetary Change*, **56(3)**, 371-386.

Gruza, G.V. and A.V. Mescherskaya, 2008: Changes in Russian climate for the period of instrumental observations. In: *Assessment Report on Climate Change and Its Consequences in Russian Federation: Vol. 1 Climate Change* [Meleshko, V.P. (ed.)]. Federal Service for Hydrometeorology and Environmental Monitoring (ROSHYDROMET), Moscow, Russia, pp. 31-87.

Guis, H., C. Caminade, C. Calvete, A.P. Morse, A. Tran, and M. Baylis, 2012: Modelling the effects of past and future climate on the risk of bluetongue emergence in Europe. *Journal of the Royal Society Interface*, **9(67)**, 339-350.

Guzman, H.M., S. Benfield, O. Breedy, and J.M. Mair, 2008: Broadening reef protection across the Marine Conservation Corridor of the Eastern Tropical Pacific: distribution and diversity of reefs in Las Perlas Archipelago, Panama. *Environmental Conservation*, **35(1)**, 46-54.

Ha, J., H. Kim, and S. Hajat, 2011: Effect of previous-winter mortality on the association between summer temperature and mortality in South Korea. *Enivronmental Health Perspectives*, **119**, 542-546.

Haeberli, W. and M. Beniston, 1998: Climate change and its impacts on glaciers and permafrost in the Alps. *Ambio*, **27(4)**, 258-265.

Haeberli, W. and R. Hohmann, 2008: Climate, glaciers and permafrost in the Swiss Alps 2050: scenarios, consequences and recommendations. In: *Proceedings Ninth International Conference on Permafrost: University of Alaska, Fairbanks, Alaska, June 29-July 3, 2008* [Kane, D.L. and K.M. Hinkel (eds.)]. Institute of Northern Engineering, University of Alaska, Fairbanks, Alaska, pp. 607-612.

Haigh, I., R. Nicholls, and N. Wells, 2010: Assessing changes in extreme sea levels: application to the English Channel, 1900-2006. *Continental Shelf Research*, **30(9)**, 1042-1055.

Haigh, I., M. Eliot, C. Pattiaratchi, and T. Wahl, 2011: Regional changes in mean sea level around Western Australia between 1897 and 2008. In: *Coasts and Ports 2011: Diverse and Developing: Proceedings of the 20th Australasian Coastal and Ocean Engineering Conference and the 13th Australasian Port and Harbour Conference*. Engineers Australia, Barton, ACT, Australia, pp. 280-285.

Halpern, B.S., S. Walbridge, K.A. Selkoe, C.V. Kappel, F. Micheli, C. D'agrosa, J.F. Bruno, K.S. Casey, C. Ebert, H.E. Fox, R. Fujita, D. Heinemann, H.S. Lenihan, E.M.P. Madin, M.T. Perry, E.R. Selig, M. Spalding, R. Steneck, and R. Watson, 2008: A global map of human impact on marine ecosystems. *Science*, **319(5865)**, 948-952.

Handmer, J., Y. Honda, Z.W. Kundzewicz, N. Arnell, G. Benito, J. Hatfield, I.F. Mohamed, P. Peduzzi, S. Wu, B. Sherstyukov, K. Takahashi, and Z. Yan, 2012: Changes in impacts of climate extremes. Human systems and ecosystems. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 231-290.

Hansen, B.B., V. Grøtan, R. Aanes, B.E. Sæther, A. Stien, E. Fuglei, R.A. Ims, N.G. Yoccoz, and Å.Ø. Pedersen, 2013: Climate events synchronize the dynamics of a resident vertebrate community in the high Arctic. *Science*, **339(6117)**, 313-315.

Hansen, J., M. Sato, and R. Ruedy, 2012: Perception of climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **109(37)**, E2415-E2423.

Hardoy, J. and G. Pandiella, 2009: Urban poverty and vulnerability to climate change in Latin America. *Environment and Urbanization*, **21(1)**, 203-224.

Harley, C.D., 2011: Climate change, keystone predation, and biodiversity loss. *Science*, **334(6059)**, 1124-1127.

Hawkins, S.J., P.J. Moore, M.T. Burrows, E. Poloczanska, N. Mieszkowska, R.J.H. Herbert, S.R. Jenkins, R.C. Thompson, M.J. Genner, and A.J. Southward, 2008: Complex interactions in a rapidly changing world: responses of rocky shore communities to recent climate change. *Climate Research*, **37**, 123-133.

Hayes, J. and A. Goonetilleke, 2012: Building community resilience – learning from the 2011 floods in Southeast Queensland, Australia. In: *8th Annual Conference of International Institute for Infrastructure, Renewal and Reconstruction: International Conference on Disaster Management (IIIRR 2012)* [Kakimoto, R. and F. Yamada (eds.)], Kumamoto University, Kumamoto, Japan, pp. 51-60.

Hecky, R.E., R. Mugidde, P.S. Ramlal, M.R. Talbot, and G.W. Kling, 2010: Multiple stressors cause rapid ecosystem change in Lake Victoria. *Freshwater Reviews*, **55**, 19-42.

Hedenås, H., H. Olsson, C. Jonasson, J. Bergstedt, U. Dahlberg, and T.V. Callaghan, 2011: Changes in tree growth, biomass and vegetation over a 13-year period in the Swedish sub-Arctic. *AMBIO: A Journal of the Human Environment*, **40(6)**, 672-682.

Hegerl, G.C., O. Hoegh-Guldberg, G. Casassa, M.P. Hoerling, R.S. Kovats, C. Parmesan, D.W. Pierce, and P.A. Stott, 2010: Good practice guidance paper on detection and attribution related to anthropogenic climate change. In: *Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Detection and Attribution of Anthropogenic Climate Change* [Stocker, T.F., C.B. Field, D. Qin, V. Barros, G.-K. Plattner, M. Tignor, P.M. Midgley, and K.L. Ebi (eds.)]. IPCC Working Group I Technical Support Unit, University of Bern, Bern, Switzerland, pp. 1-8.

Held, I., T. Delworth, J. Lu, K. Findell, and T. Knutson, 2005: Simulation of Sahel drought in the 20th and 21st centuries. *Proceedings of the National Academy of Sciences of the United States of America*, **102(50)**, 17891-17896.

Helmuth, B., C.D. Harley, P.M. Halpin, M. O'Donnell, G.E. Hofmann, and C.A. Blanchette, 2002: Climate change and latitudinal patterns of intertidal thermal stress. *Science*, **298(5595)**, 1015-1017.

Helmuth, B., N. Mieszkowska, P. Moore, and S.J. Hawkins, 2006: Living on the edge of two changing worlds: forecasting the responses of rocky intertidal ecosystems to climate change. *Annual Review of Ecology, Evolution, and Systematics*, **37**, 373-404.

Hémon, D. and E. Jougla, 2003: *Surmortalité liée à la Canicule d'Août 2003: Rapport d'Étape. Estimation de la Surmortalite et Principales Caracteristiques Epidemiologiques*. Rapport remis au Ministre de la Santé, de la Famille et des Personnes Handicapées le 25 Septembre 2003, Institut National de la Santé et de la Recherche Médicale (INSERM), Paris, France, 59 pp.

Hemp, A., 2005: Climate change-driven forest fires marginalize the impact of ice cap wasting on Kilimanjaro. *Global Change Biology*, **11(7)**, 1013-1023.

Hendrix, C.S. and S.M. Glaser, 2007: Trends and triggers: climate, climate change and civil conflict in Sub-Saharan Africa. *Political Geography*, **26(6)**, 695-715.

Hendrix, C.S. and I. Salehyan, 2012: Climate change, rainfall, and social conflict in Africa. *Journal of Peace Research*, **49**, 35-50.

Hennessy, K.J., P.H. Whetton, K. Walsh, I.N. Smith, J.M. Bathols, M. Hutchinson, and J. Sharples, 2008: Climate change effects on snow conditions in mainland Australia and adaptation at ski resorts through snowmaking. *Climate Research*, **35(3)**, 255-270.

Henry, G.H.R. and S. Elmendorf, 2010: Greening of the Arctic. In: *Arctic Biodiversity Trends 2010 – Selected Indicators of Change*. Arctic Council, Conservation of Arctic Flora and Fauna Programme (CAFF), CAFF International Secretariat, Akureyri, Iceland, pp. 62-64.

Herman-Mercer, N., P.F. Schuster, and K.B. Maracle, 2011: Indigenous observations of climate change in the Lower Yukon River Basin, Alaska. *Human Organization*, **70**, 244-252.

Hermant, M., J. Lobry, S. Bonhommeau, J. Poulard, and O. Le Pape, 2010: Impact of warming on abundance and occurrence of flatfish populations in the Bay of Biscay (France). *Journal of Sea Research*, **64(1)**, 45-53.

Hiddink, J.G. and R. ter Hofstede, 2008: Climate induced increases in species richness of marine fishes. *Global Change Biology*, **14(3)**, 453-460.

Hinzman, L.D., N.D. Bettez, W.R. Bolton, F.S. Chapin, M.B. Dyurgerov, C.L. Fastie, B. Griffith, R.D. Hollister, A. Hope, and H.P. Huntington, 2005: Evidence and implications of recent climate change in northern Alaska and other Arctic regions. *Climatic Change*, **72(3)**, 251-298.

Hockey, P.A.R. and G.F. Midgley, 2009: Avian range changes and climate change. A cautionary tale from the Cape Peninsula. *Ostrich*, **80**, 29-34.

Hockey, P.A.R., C. Sirami, A.R. Ridley, G.F. Midgley, and H.A. Babiker, 2011: Interrogating recent range changes in South African birds. Confounding signals from land use and climate change present a challenge for attribution. *Diversity and Distributions*, **17**, 254-261.

Hoegh-Guldberg, O., 1999: Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research*, **50(8)**, 839-866.

Hoegh-Guldberg, O. and J.F. Bruno, 2010: The impact of climate change on the world's marine ecosystems. *Science*, **328(5985)**, 1523-1528.

Hoegh-Guldberg, O. and G.J. Smith, 1989: The effect of sudden changes in temperature, light and salinity on the population-density and export of zooxanthellae from the reef corals *Stylophora-pistillata* Esper and *Seriatopora-hystrix* Dana. *Journal of Experimental Marine Biology and Ecology*, **129(3)**, 279-303.

Hoegh-Guldberg, O., P.J. Mumby, A.J. Hooten, R.S. Steneck, P. Greenfield, E. Gomez, C.D. Harvell, P.F. Sale, A.J. Edwards, K. Caldeira, N. Knowlton, C.M. Eakin, R. Iglesias-Prieto, N. Muthiga, R.H. Bradbury, A. Dubi, and M.E. Hatziolos, 2007: Coral reefs under rapid climate change and ocean acidification. *Science*, **318(5857)**, 1737-1742.

Hoegh-Guldberg, O., G. Hegerl, T. Root, F. Zwiers, P. Stott, D. Pierce, and M. Allen, 2011: Difficult but not impossible. *Nature Climate Change*, **1(2)**, 72-72.

Hoerling, M., J. Hurrell, J. Eischeid, and A. Phillips, 2006: Detection and attribution of twentieth-century northern and southern African rainfall change. *Journal of Climate*, **19(16)**, 3989-4008.

Hoinka, K.P., A. Carvalho, and A.I. Miranda, 2009: Regional-scale weather patterns and wildland fires in central Portugal. *International Journal of Wildland Fire*, **18(1)**, 36-49.

Hollowed, A.B., S.R. Hare, and W.S. Wooster, 2001: Pacific Basin climate variability and patterns of Northeast Pacific marine fish production. *Progress in Oceanography*, **49**, 257-282.

Horowitz, J., 2009: The income-temperature relationship in a cross-section of countries and its implications for predicting the effects of global warming. *Environmental and Resource Economics*, **44(4)**, 475-493.

Houze Jr., R.A., K.L. Rasmussen, S. Medina, S.R. Brodzik, and U. Romatschke, 2011: Anomalous atmospheric events leading to the summer 2010 floods in Pakistan. *Bulletin of the American Meteorological Society*, **92(3)**, 291-298.

Hovelsrud, G.K., M. McKenna, and H.P. Huntington, 2008: Marine mammal harvests and other interactions with humans. *Ecological Applications*, **18(2 Suppl.)**, S135-S147.

Howden, S.M., S.J. Crimp, and R. Nelson, 2010: Australian agriculture in a climate of change. In: *Managing Climate Change: Papers from the GREENHOUSE 2009 Conference* [Jubb, I., P. Holper, and W. Cai (eds.)]. CSIRO Publishing, Collingwood, Australia, pp. 101-111.

Hoyos, L.E., A.M. Cingolani, M.R. Zak, M.V. Vaieretti, D.E. Gorla, and M.R. Cabido, 2013: Deforestation and precipitation patterns in the arid Chaco forests of central Argentina. *Applied Vegetation Science*, **16(2)**, 260-271.

Hoyos, N., J. Escobar, J.C. Restrepo, A.M. Arango, and J.C. Ortiz, 2013: Impact of the 2010-2011 La Niña phenomenon in Colombia, South America: the human toll of an extreme weather event. *Applied Geography*, **39**, 16-25.

Hsiang, S.M., K.C. Meng, and M.A. Cane, 2011: Civil conflicts are associated with the global climate. *Nature*, **476(7361)**, 438-441.

Hsiang, S.M., M. Burke, and E. Miguel, 2013: Quantifying the influence of climate on human conflict. *Science*, **341(6151)**, 1235367, doi:10.1126/science.1235367.

Hsieh, C.-h., C. Reiss, W. Watson, M.J. Allen, J.R. Hunter, R.N. Lea, R.H. Rosenblatt, P.E. Smith, and G. Sugihara, 2005: A comparison of long-term trends and variability in populations of larvae of exploited and unexploited fishes in the Southern California region. A community approach. *Progress in Oceanography*, **67(1)**, 160-185.

Hsieh, C.-h., C.S. Reiss, R.P. Hewitt, and G. Sugihara, 2008: Spatial analysis shows that fishing enhances the climatic sensitivity of marine fishes. *Canadian Journal of Fisheries and Aquatic Sciences*, **65**, 947-961.

Huang, X., M. Sillanpää, E.T. Gjeesing, and P.R. Vogt, 2009: Water quality in the Tibetan Plateau: major ions and trace elements in the headwaters of four major Asian rivers. *Science of the Total Environment*, **407(24)**, 6242-6254.

Huggel, C., L. Blaškovičová, H. Breien, P. Dobesberger, R. Frauenfelder, B.G. Kalsnes, A. Solheim, M. Stankoviansky, K. Hagen, and K. Kronholm, 2011: Landslide and rock slope failures. In: *Impacts of Climate Change on Snow, Ice, and Permafrost in Europe: Observed Trends, Future Projections, and Socio-Economic Relevance* [Voigt, T., H.M. Füssel, I. Gärtner-Roer, C. Huggel, C. Marty, and M. Zemp (eds.)]. ETC/ACC Technical Paper 2010/13, Prepared by the European Topic Centre on Air and Climate Change (ETC/ACC) with the Department of Geography of the University of Zuerich, the WSL Institute for Snow and Avalanche Research (SLF) Davos and others for the European Environment Agency (EEA), ETC/ACC, Bilthoven, Netherlands, pp. 95-101.

Huggel, C., S. Allen, P. Deline, L. Fischer, J. Noetzli, and L. Ravanel, 2012a: Ice thawing, mountains falling – are alpine rock slope failures increasing? *Geology Today*, **28(3)**, 102-108.

Huggel, C., J.J. Clague, and O. Korup, 2012b: Is climate change responsible for changing landslide activity in high mountains? *Earth Surface Processes and Landforms*, **37**, 77-91.

Hulme, M., 2008: Geographical work at the boundaries of climate change. *Transactions of the Institute of British Geographers*, **33(1)**, 5-11.

Hulme, M., S.J. O'Neill, and S. Dessai, 2011: Is weather event attribution necessary for adaptation funding? *Science*, **334**, 764-765.

Hunt, G.L., B.M. Allen, R.P. Angliss, T. Baker, N. Bond, G. Buck, G.V. Byrd, K.O. Coyle, A. Devol, D.M. Eggers, L. Eisner, R. Feely, S. Fitzgerald, L.W. Fritz, E.V. Gritsay, C. Ladd, W. Lewis, J. Mathis, C.W. Mordy, F. Mueter, J. Napp, E. Sherr, D. Shull, P. Stabeno, M.A. Stepanenko, S. Strom, and T.E. Whitledge, 2010: Status and trends of the Bering Sea region, 2003-2008. In: *Marine Ecosystems of the North Pacific Ocean, 2003-2008.* [McKinnell, S.M. and M.J. Dagg (eds.)]. PICES Special Publication 4, North Pacific Marine Science Organization (PICES) at the Institute of Ocean Sciences, Sidney, BC, Canada, pp. 196-267.

Huntington, H., T. Callaghan, S. Fox, and I. Krupnik, 2004: Matching traditional and scientific observations to detect environmental change: a discussion on Arctic terrestrial ecosystems. *Ambio*, **13**, 18-23.

Huss, M., 2011: Present and future contribution of glacier storage change to runoff from macroscale drainage basins in Europe. *Water Resources Research*, **47**, W07511, doi:10.1029/2010WR010299.

IntraRisk, 2002: *Development of Loss Relativities for Wind Resistive Features of Residential Structures.* Version 2.2, Prepared by Applied Research Associates, Inc., IntraRisk Division, for the Florida Department of Community Affairs, Tallassee, FL, USA, 294 pp.

IPCC, 2007a: Summary for policymakers. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.]. Cambridge University Press, Cambridge, UK, pp. 7-22.

IPCC, 2007b: Summary for Policymakers. In: *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K. and A. Reisinger (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, P.M. Midgley (ed.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

Isaac, M. and D.P. van Vuuren, 2009: Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. *Energy Policy*, **37(2)**, 507-521.

Jaggard, K., A. Qi, and M. Semenov, 2007: The impact of climate change on sugarbeet yield in the UK: 1976-2004. *The Journal of Agricultural Science*, **145(4)**, 367-375.

Jellyman, D.J., D.J. Booker, and E. Watene, 2009: Recruitment of *Anguilla* spp. glass eels in the Waikato River, New Zealand. Evidence of declining migrations? *Journal of Fish Biology*, **74(9)**, 2014-2033.

Jenkins, G.S., A.T. Gaye, and B. Sylla, 2005: Late 20th century attribution of drying trends in the Sahel from the Regional Climate Model (RegCM3). *Geophysical Research Letters*, **32(22)**, L22705, doi:10.1029/2005GL024225.

Jenouvrier, S., H. Weimerskirch, C. Barbraud, and Y.H. Park, 2005: Evidence of a shift in the cyclicity of Antarctic seabird dynamics linked to climate. *Proceedings of the Royal Society B*, **272(1566)**, 887-895.

Jeong, S., C.H. Ho, H.J. Gim, and M. Brown, 2011: Phenology shifts at start vs. end of growing season in temperate vegetation over the Northern Hemisphere for the period 1982-2008. *Global Change Biology*, **17(7)**, 2385-2399.

Jia, G.J., H.E. Epstein, and D.A. Walker, 2009: Vegetation greening in the Canadian Arctic related to decadal warming. *Journal of Environmental Monitoring*, **11(12)**, 2231-2238.

Jiang, Y., T.H. Dixon, and S. Wdowinski, 2010: Accelerating uplift in the North Atlantic region as an indicator of ice loss. *Nature Geoscience*, **3(6)**, 404-407.

Jin, M., C. Deal, J. Wang, and C.P. McRoy, 2009: Response of lower trophic level production to long-term climate change in the southeastern Bering Sea. *Journal of Geophysical Research*, **114(C4)**, C04010, doi:10.1029/2008JC005105.

Johnson, C.R., S.C. Banks, N.S. Barrett, F. Cazassus, P.K. Dunstan, G.J. Edgar, S.D. Frusher, C. Gardner, M. Haddon, and F. Helidoniotis, 2011: Climate change cascades: shifts in oceanography, species' ranges and subtidal marine community dynamics in eastern Tasmania. *Journal of Experimental Marine Biology and Ecology*, **400(1)**, 17-32.

Jomelli, V., V.P. Pech, C. Chochillon, and D. Brunstein, 2004: Geomorphic variations of debris flows and recent climatic change in the French Alps. *Climatic Change*, **64(1)**, 77-102.

Jomelli, V., V. Favier, A. Rabatel, D. Brunstein, G. Hoffmann, and B. Francou, 2009: Fluctuations of glaciers in the tropical Andes over the last millennium and palaeoclimatic implications: a review. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **281(3)**, 269-282.

Jones, B.F. and B.A. Olken, 2010: Climate shocks and exports. *American Economic Review*, **100(2)**, 454-459.

Jones, R., O. Hoegh-Guldberg, A. Larkum, and U. Schreiber, 1998: Temperature induced bleaching of corals begins with impairment to the carbon dioxide fixation mechanism of zooxanthellae. *Plant, Cell and Environment*, **21**, 1219-1230.

Jump, A.S., J. Hunt, and J. Peñuelas, 2006: Rapid climate change-related growth decline at the southern range-edge of *Fagus sylvatica*. *Global Change Biology*, **12(11)**, 2163-2174.

Jump, A.S., T. Huang, and C. Chou, 2012: Rapid altitudinal migration of mountain plants in Taiwan and its implications for high altitude biodiversity. *Ecography*, **35(3)**, 204-210.

Jury, M.R. and A. Winter, 2010: Warming of an elevated layer over the Caribbean. *Climatic Change*, **99(1-2)**, 247-259.

Kääb, A., R. Frauenfelder, and I. Roer, 2007: On the response of rockglacier creep to surface temperature increase. *Global and Planetary Change*, **56(1)**, 172-187.

Kääb, A., E. Berthier, C. Nuth, J. Gardelle, and Y. Arnaud, 2012: Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas. *Nature*, **488(7412)**, 495-498.

Karl, T.R., J.M. Melillo, and T.C. Peterson, 2009: *Global Climate Change Impacts in the United States.* Cambridge University Press, Cambridge, UK and New York, NY, USA, 188 pp.

Kasischke, E.S., D.L. Verbyla, T.S. Rupp, A.D. McGuire, K.A. Murphy, R. Jandt, J.L. Barnes, E.E. Hoy, P.A. Duffy, and M. Calef, 2010: Alaska's changing fire regime-implications for the vulnerability of its boreal forests. *Canadian Journal of Forest Research*, **40(7)**, 1313-1324.

Kawachi, I., B.P. Kennedy, and R.G. Wilkinson, 1999: Crime: social disorganization and relative deprivation. *Social Science & Medicine*, **48(6)**, 719-731.

Kay, A.L., S.M. Crooks, P. Pall, and D.A. Stone, 2011: Attribution of autumn/winter 2000 flood risk in England to anthropogenic climate change: a catchment-based study. *Journal of Hydrology*, **406(1)**, 97-112.

Kearney, M.R., N.J. Briscoe, D.J. Karoly, W.P. Porter, M. Norgate, and P. Sunnucks, 2010: Early emergence in a butterfly causally linked to anthropogenic warming. *Biology Letters*, **6(5)**, 674-677.

Keatley, M.R. and I.L. Hudson, 2012: Detecting change in an Australian flowering record: comparisons of linear regression and cumulative sum analysis change point analysis. *Austral Ecology*, **37(7)**, 825-835.

Keith, D.A., S. Rodoreda, and M. Bedward, 2010: Decadal change in wetland-woodland boundaries during the late 20th century reflects climatic trends. *Global Change Biology*, **16(8)**, 2300-2306.

Kelly, A.E. and M.L. Goulden, 2008: Rapid shifts in plant distribution with recent climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **105(33)**, 11823-11826.

Kharuk, V.I., S.T. Im, M.L. Dvinskaya, and K.I. Ranson, 2010: Climate-induced mountain tree-line evolution in southern Siberia. *Scandinavian Journal of Forest Research*, **25(5)**, 446-454.

Kiesecker, J.M., 2011: Global stressors and the global decline of amphibians: tipping the stress immunocompetency axis. *Ecological Research*, **26(5)**, 897-908.

Killeen, T.J., A. Guerra, M. Calzada, L. Correa, V. Calderon, L. Soria, B. Quezada, and M.K. Steininger, 2008: Total historical land-use change in Eastern Bolivia: who, where, when, and how much? *Ecology and Society*, **13(1)**, 36, www.ecologyandsociety.org/vol13/iss1/art36/.

Knutson, T.R., J.L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J.P. Kossin, A. Srivastava, and M. Sugi, 2010: Tropical cyclones and climate change. *Nature Geoscience*, **3(3)**, 157-163.

Komori, D., S. Nakamura, M. Kiguchi, A. Nishijima, D. Yamazaki, S. Suzuki, A. Kawasaki, K. Oki, and T. Oki, 2012: Characteristics of the 2011 Chao Phraya River flood in Central Thailand. *Hydrological Research Letters*, **6**, 41-46.

Kopp, R.E., J.X. Mitrovica, S.M. Griffies, J. Yin, C.C. Hay, and R.J. Stouffer, 2010: The impact of Greenland melt on local sea levels: a partially coupled analysis of dynamic and static equilibrium effects in idealized water-hosing experiments. *Climatic Change*, **103(3-4)**, 619-625.

Korup, O., T. Görüm, and Y. Hayakawa, 2012: Without power? Landslide inventories in the face of climate change. *Earth Surface Processes and Landforms*, **37(1)**, 92-99.

Koutsias, N., M. Arianoutsou, A.S. Kallimanis, G. Mallinis, J.M. Halley, and P. Dimopoulos, 2012: Where did the fires burn in Peloponnisos, Greece the summer of 2007? Evidence for a synergy of fuel and weather. *Agricultural and Forest Meteorology*, **156(0)**, 41-53.

Kovach, R.P., A.J. Gharrett, and D.A. Tallmon, 2012: Genetic change for earlier migration timing in a pink salmon population. *Proceedings of the Royal Society B*, **279(1743)**, 3870-3878.

Kovats, R.S., D.H. Campbell-Lendrum, A.J. McMichael, A. Woodward, and J.S. Cox, 2001: Early effects of climate change: do they include changes in vector-borne disease? *Philosophical Transactions of the Royal Society B*, **356**, 1057-1068.

Krauss, K.W., D.R. Cahoon, J.A. Allen, K.C. Ewel, J.C. Lynch, and N. Cormier, 2010: Surface elevation change and susceptibility of different mangrove zones to sea-level rise on Pacific high islands of Micronesia. *Ecosystems*, **13(1)**, 129-143.

Krepper, C.M. and G.V. Zucarelli, 2010: Climatology of water excesses and shortages in the La Plata Basin. *Theoretical and Applied Climatology*, **102(1-2)**, 13-27.

Krepper, C.M., N.O. Garcia, and P.D. Jones, 2008: Low-frequency response of the upper Parana basin. *International Journal of Climatology*, **28(3)**, 351-360.

Krishnan, P., S. Dam Roy, G. George, R.C. Srivastava, A. Anand, S. Murugesan, M. Kaliyamoorthy, N. Vikas, and R. Soundararajan, 2011: Elevated sea surface temperature during May 2010 induces mass bleaching of corals in the Andaman. *Current Science*, **100(1)**, 111-117.

Kristensen, K., K. Schelde, and J.E. Olesen, 2011: Winter wheat yield response to climate variability in Denmark. *The Journal of Agricultural Science*, **149(1)**, 33-47.

Kriz, B., M. Maly, C. Benes, and M. Daniel, 2012: Epidemiology of tick-borne encephalitis in the Czech Republic 1970-2008. *Vector-Borne and Zoonotic Diseases*, **12(11)**, 994-999.

Krupnik, I. and G.C. Ray, 2007: Pacific walruses, indigenous hunters, and climate change: bridging scientific and indigenous knowledge. *Deep Sea Research Part II: Topical Studies in Oceanography*, **54**, 2946-2957.

Krushelnycky, P.D., L.L. Loope, T.W. Giambelluca, F. Starr, K. Starr, D.R. Drake, A.D. Taylor, and R.H. Robichaux, 2013: Climate-associated population declines reverse recovery and threaten future of an iconic high-elevation plant. *Global Change Biology*, **19(3)**, 911-922.

Kucharik, C.J. and S.P. Serbin, 2008: Impacts of recent climate change on Wisconsin corn and soybean yield trends. *Environmental Research Letters*, **3(3)**, 034003, doi:10.1088/1748-9326/3/3/034003.

Kumar, A., M. Chen, M. Hoerling, and J. Eischeid, 2013: Do extreme climate events require extreme forcings? *Geophysical Research Letters*, **40(13)**, 3340-3445.

Kundzewicz, Z.W. and V. Krysanova, 2010: Climate change and stream water quality in the multi-factor context. *Climatic Change*, **103(3-4)**, 353-362.

Kundzewicz, Z.W., I. Pińskwar, and G.R. Brakenridge, 2013: Large floods in Europe, 1985-2009. *Hydrological Sciences Journal*, **58(1)**, 1-7.

Lacombe, G., M. McCartney, and G. Forkuor, 2012: Drying climate in Ghana over the period 1960-2005: evidence from the resampling-based Mann-Kendall test at local and regional levels. *Hydrological Sciences Journal*, **57(8)**, 1594-1609.

Laidler, G.J., 2006: Inuit and scientific perspectives on the relationship between sea ice and climate change: the ideal complement? *Climatic Change*, **78(2-4)**, 407-444.

Laidre, K.L., I. Stirling, L.F. Lowry, O. Wiig, M.O. Heide-Jørgensen, and S.H. Ferguson, 2008: Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecological Applications*, **18(2)**, 97-125.

Lalande, F., S. Legrain, A.-J. Valleron, and D. Meyniel, 2003: *Mission d'Expertise et d'Évaluation du Système de Santé pendant la Canicule 2003.* Ministère de la Santé, de la Famille, et des Personnes Handicapées, Paris, France, 174 pp.

Lamela-Silvarrey, C., C. Fernández, R. Anadón, and J. Arrontes, 2012: Fucoid assemblages on the north coast of Spain: past and present (1977-2007). *Botanica Marina*, **55(3)**, 199-207.

Lampis, A., 2010: Challenges to adaptation for risk-prone coastal livelihoods in Tumaco, Pacific Coast (Colombia). *UGEC Viewpoints*, No. 3, March 2010, 18-22.

Lantuit, H., P.P. Overduin, N. Couture, S. Wetterich, F. Aré, D. Atkinson, J. Brown, G. Cherkashov, D. Drozdov, D. Forbes, A. Graves-Gaylord, M. Grigoriev, H.W. Hubberten, J. Jordan, T. Jorgenson, R. Ødegård, S. Ogorodov, W. Pollard, V. Rachold, S. Sedenko, S. Solomon, F. Steenhuisen, I. Streletskaya, and A. Vasiliev, 2011: The Arctic coastal dynamics database: a new classification scheme and statistics on Arctic permafrost coastlines. *Estuaries and Coasts*, **35(2)**, 383-400.

Lasram, F.B.R. and D. Mouillot, 2009: Increasing southern invasion enhances congruence between endemic and exotic Mediterranean fish fauna. *Biological Invasions*, **11(3)**, 697-711.

Laternser, M. and M. Schneebeli, 2002: Temporal trend and spatial distribution of avalanche activity during the last 50 years in Switzerland. *Natural Hazards*, **27(3)**, 201-230.

Laybourn-Parry, J., 2003: Polar limnology, the past, the present and the future. In: *Antarctic Biology in a Global Context* [Huiskes, A.H.L., W.W.C. Gieskes, J. Rozema, R.M.L. Schorno, S.M. van der Vies, and W.J. Wolff (eds.)]. Backhuys Publishers, Leiden, Netherlands, pp. 321-329.

Le Polain de Waroux, Y. and E.F. Lambin, 2012: Monitoring degradation in arid and semi-arid forests and woodlands: the case of the Argan woodlands (Morocco). *Applied Geography*, **32(2)**, 777-786.

Le Quéré, C., M.R. Raupach, J.G. Canadell, and G. Marland, 2009: Trends in the sources and sinks of carbon dioxide. *Nature Geoscience*, **2**, 831-836.

Leadley, P., H.M. Pereira, R. Alkemade, J.F. Fernandez-Manjarrés, V. Proença, J.P.W. Scharlemann, and M.J. Walpole, 2010: *Biodiversity Scenarios: Projections of 21st Century Change in Biodiversity and Associated Ecosystem Services.* CBD Technical Series No. 50, Technical Report for the Global Biodiversity Outlook 3, Secretariat of the Convention on Biological Diversity, Montreal, QC, Canada, 132 pp.

Leatherman, S.P., K. Zhang, and B.C. Douglas, 2000: Sea level rise shown to drive coastal erosion. *Eos, Transactions of the American Geophysical Union*, **81(6)**, 55-57.

Leblanc, M.J., P. Tregoning, G. Ramillien, S.O. Tweed, and A. Fakes, 2009: Basin-scale, integrated observations of the early 21st century multiyear drought in southeast Australia. *Water Resources Research*, **45(4)**, doi:10.1029/2008WR007333.

Lenoir, J., J.C. Gegout, P.A. Marquet, P. de Ruffray, and H. Brisse, 2008: A significant upward shift in plant species optimum elevation during the 20th century. *Science*, **320(5884)**, 1768-1771.

Lenton, T.M., 2011: Early warning of climate tipping points. *Nature Climate Change*, **1(4)**, 201-209.

Lenton, T.M., H. Held, E. Kriegler, J.W. Hall, W. Lucht, S. Rahmstorf, and H.J. Schellnhuber, 2008: Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences of the United States of America*, **105(6)**, 1786-1793.

Levin, L.A., W. Ekau, A.J. Gooday, F. Jorissen, J.J. Middelburg, S.W.A. Naqvi, C. Neira, N.N. Rabalais, and J. Zhang, 2009: Effects of natural and human-induced hypoxia on coastal benthos. *Biogeosciences*, **6(10)**, 2063-2098.

Li, Z.X., Y.Q. He, T. Pu, W.X. Jia, X.Z. He, H.X. Pang, N.N. Zhang, Q. Liu, S.J. Wang, G.F. Zhu, S.X. Wang, L. Chang, J.K. Du, and H.J. Xin, 2010: Changes of climate, glaciers and runoff in China's monsoonal temperate glacier region during the last several decades. *Quaternary International*, **218(1-2)**, 13-28.

Lima, F.P. and D.S. Wethey, 2012: Three decades of high-resolution coastal sea surface temperatures reveal more than warming. *Nature Communications*, **3(704)**, 1-13.

Lima, F.P., P.A. Ribeiro, N. Queiroz, S.J. Hawkins, and A.M. Santos, 2007: Do distributional shifts of northern and southern species of algae match the warming pattern? *Global Change Biology*, **13(12)**, 2592-2604.

Ling, S.D., 2008: Range expansion of a habitat-modifying species leads to loss of taxonomic diversity: a new and impoverished reef state. *Oecologia*, **156(4)**, 883-894.

Ling, S.D., C.R. Johnson, S. Frusher, and K. Ridgway, 2009a: Overfishing reduces resilience of kelp beds to climate-driven catastrophic phase shift. *Proceedings of the National Academy of Sciences of the United States of America*, **106(52)**, 22341-22345.

Ling, S.D., C.R. Johnson, K. Ridgway, A.J. Hobday, and M. Haddon, 2009b: Climate-driven range extension of a sea urchin: inferring future trends by analysis of recent population dynamics. *Global Change Biology*, **15(3)**, 719-731.

Litzow, M.A., J.D. Urban, and B.J. Laurel, 2008: Increased spatial variance accompanies reorganization of two continental shelf ecosystems. *Ecological Applications*, **18(6)**, 1331-1337.

Livingstone, D.M., R. Adrian, T. Blenckner, G. George, and G.A. Weyhenmeyer, 2010: Lake ice phenology. In: *The Impact of Climate Change on European Lakes* [George, D.G. (ed.)]. Aquatic Ecology Series 4, Springer Science, Dordrecht, Netherlands, pp. 51-61.

Lloyd, A.H., A.G. Bunn, and L. Berner, 2011: A latitudinal gradient in tree growth response to climate warming in the Siberian taiga. *Global Change Biology*, **17(5)**, 1935-1945.

Lobell, D.B. and C.B. Field, 2007: Global scale climate – crop yield relationships and the impacts of recent warming. *Environmental Research Letters*, **2(1)**, 014002, doi:10.1088/1748-9326/2/1/014002.

Lobell, D.B., W. Schlenker, and J. Costa-Roberts, 2011: Climate trends and global crop production since 1980. *Science*, **333(6042)**, 616-620.

Loriaux, T. and G. Casassa, 2013: Evolution of glacial lakes from the Northern Patagiona Icefield and terrestrial water storage in a sea-level rise context. *Global and Planetary Change*, **102(3)**, 33-40.

Lotze, H.K., H.S. Lenihan, B.J. Bourque, R.H. Bradbury, R.G. Cooke, M.C. Kay, S.M. Kidwell, M.X. Kirby, C.H. Peterson, and J.B.C. Jackson, 2006: Depletion, degradation, and recovery potential of estuaries and coastal seas. *Science*, **312(5781)**, 1806-1809.

Lucey, S.M. and J.A. Nye, 2010: Shifting species assemblages in the Northeast US continental shelf large marine ecosystem. *Marine Ecology Progress Series*, **415**, 23-33.

Ludwig, F., S.P. Milroy, and S. Asseng, 2009: Impacts of recent climate change on wheat production systems in Western Australia. *Climatic Change*, **92(3-4)**, 495-517.

Lugon, R. and M. Stoffel, 2010: Rock-glacier dynamics and magnitude-frequency relations of debris flows in a high-elevation watershed: Ritigraben, Swiss Alps. *Global and Planetary Change*, **73(3-4)**, 202-210.

Luyssaert, S., P. Ciais, S.L. Piao, E.D. Schulze, M. Jung, S. Zaehle, M.J. Schelhaas, M. Reichstein, G. Churkina, and D. Papale, 2010: The European carbon balance. Part 3: forests. *Global Change Biology*, **16(5)**, 1429-1450.

Ma, E.Q., M.J. Guinery, P. McCarthy, and R. Shaw, 2012: Australian floods and their impact on insurance. In: *Extreme Events and Insurance: 2011 Annus Horribilis* [Courbage, C. and W.R. Stahel (eds.)]. The Geneva Reports – Risk and Insurance Research No. 5, The Geneva Association, Geneva, Switzerland, pp. 81-91.

Ma, T. and C. Zhou, 2012: Climate-associated changes in spring plant phenology in China. *International Journal of Biometeorology*, **56(2)**, 269-275.

Mack, M.C., M.S. Bret-Harte, T.N. Hollingsworth, R.R. Jandt, E.A.G. Schuur, G.R. Shaver, and D.L. Verbyla, 2011: Carbon loss from an unprecedented Arctic tundra wildfire. *Nature*, **475(7357)**, 489-492.

Maclean, K. and L. Cullen, 2009: Research methodologies for the co-production of knowledge for environmental management in Australia. *Journal of the Royal Society of New Zealand*, **39**, 205-208.

Magrin, G.O., M.I. Travasso, W.E. Baethgen, M.O. Grondona, A. Giménez, G. Cunha, J.P. Castaño, and G.R. Rodriguez, 2007: Past and future changes in climate and their impacts on annual crops yield in south east South America. In: *IPCC TGICA Expert Meeting: Integrating Analysis of Regional Climate Change and Response Options, Nadi, Fiji, 20-22 June, 2007*. Meeting Report, Intergovernmental Panel on Climate Change (IPCC) Task Group on Data Scenario Support for Impact and Climate Analysis (TGICA), Sponsored by the Global Change System for Analysis, Research and Training (START) and The Pacific Center for Environment and Sustainable Development at the University of South Pacific (PACE/USP), IPCC TGICA, Geneva, Switzerland, pp. 121-124.

Malhi, Y., L. Aragao, D. Galbraith, C. Huntingford, R. Fisher, P. Zelazowski, S. Sitch, C. McSweeney, and P. Meir, 2009: Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences of the United States of America*, **106(49)**, 20610-20615.

Malik, N., B. Bookhagen, N. Marwan, and J. Kurths, 2011: Analysis of spatial and temporal extreme monsoonal rainfall over South Asia using complex networks. *Climate Dynamics*, **39(3-4)**, 971-987.

Mann, D.H., T.S. Rupp, M.A. Olson, and P.A. Duffy, 2012: Is Alaska's boreal forest now crossing a major ecological threshold? *Arctic, Antarctic, and Alpine Research*, **44(3)**, 319-331.

Mann, M.E. and K.A. Emanuel, 2012: Atlantic hurricane trends linked to climate change. *Eos, Transactions of the American Geophysical Union*, **87(24)**, 233-241.

Manzello, D.P., J.A. Kleypas, D.A. Budd, C.M. Eakin, P.W. Glynn, and C. Langdon, 2008: Poorly cemented coral reefs of the eastern tropical Pacific: possible insights into reef development in a high-CO_2 world. *Proceedings of the National Academy of Sciences of the United States of America*, **105(30)**, 10450-10455.

Maranz, S., 2009: Tree mortality in the African Sahel indicates an anthropogenic ecosystem displaced by climate change. *Journal of Biogeography*, **36**, 1181-1193.

Marbà, N. and C.M. Duarte, 2010: Mediterranean warming triggers seagrass (*Posidonia oceanica*) shoot mortality. *Global Change Biology*, **16(8)**, 2366-2375.

Marchiori, L., J.F. Maystadt, and I. Schumacher, 2012: The impact of weather anomalies on migration in sub-Saharan Africa. *Journal of Environmental Economics and Management*, **63(3)**, 335-374.

Marcos, M., M.N. Tsimplis, and A.G.P. Shaw, 2009: Sea level extremes in southern Europe. *Journal of Geophysical Research*, **114**, C01007, doi:10.1029/2008JC004912.

Marengo, J.A., J. Tomasella, L.M. Alves, W.R. Soares, and D.A. Rodriguez, 2011a: The drought of 2010 in the context of historical droughts in the Amazon region. *Geophysical Research Letters*, **38(12)**, L12703, doi:10.1029/2011GL047436.

Marengo, J.A., C.A. Nobre, G. Sampaio, L.F. Salazar, and L.S. Borma, 2011b: *Climate Change in the Amazon Basin: Tipping Points, Changes in Extremes, and Impacts on Natural and Human Systems.* Springer, New York, NY, USA, pp. 259-283.

Mars, J. and D. Houseknecht, 2007: Quantitative remote sensing study indicates doubling of coastal erosion rate in past 50 yr along a segment of the Arctic coast of Alaska. *Geology*, **35(7)**, 583-586.

Marsh, P., M. Russell, S. Pohl, H. Haywood, and C. Onclin, 2008: Changes in thaw lake drainage in the Western Canadian Arctic from 1950 to 2000. *Hydrological Processes*, **23(1)**, 145-158.

Marshall, B.E., 2012: Does climate change really explain changes in the fisheries productivity of Lake Kariba (Zambia-Zimbabwe)? *Transactions of the Royal Society of South Africa*, **67**, 45-51.

Martinez, R., C. Euscategui, E. Jaimes, G. Léon, and A. Quintero, 2011: Northern South America and the Tropical Andes. In: *State of the Climate in 2010* [Blunden, J., D.S. Arndt, and M.O. Baringer (eds.)]. Special Supplement to the *Bulletin of the American Meteorological Society*, **92(6)**, S186-S187.

Marty, C., 2008: Regime shift of snow days in Switzerland. *Geophysical Research Letters*, **35(12)**, L12501, doi:10.1029/2008GL033998.

Marulanda, M.C., O.D. Cardona, and A.H. Barbat, 2010: Revealing the socioeconomic impact of small disasters in Colombia using the DesInventar database. *Disasters*, **34(2)**, 552-570.

Marzeion, B., A. Jarosch, and M. Hofer, 2012: Past and future sea-level change from the surface mass balance of glaciers. *The Cryosphere Discussions*, **6(4)**, 3177-3241.

Mathiesen, S.D., B. Alfthan, R. Corell, R.B.M. Eira, I.M.G. Eira, A. Degteva, K.I. Johnsen, A. Oskal, M. Roué, M.N. Sara, E.R. Skum, E.I. Turi, and J.M. Turi, 2013: Strategies to enhance the resilience of Sámi reindeer husbandry to rapid changes in the Arctic. In: *Arctic Resilience Interim Report.* Arctic Council, Stockholm Environment Institute (SEI) and Stockholm Resilience Centre, Stockholm, Sweden, pp. 109-112.

Mavume, A.F., L. Rydberg, M. Rouault, and J.R. Lutjeharms, 2009: Climatology and landfall of tropical cyclones in the south-west Indian Ocean. *Western Indian Ocean Journal of Marine Science*, **8(1)**, 15-36.

McDowell, J.Z. and J.J. Hess, 2012: Accessing adaptation: Multiple stressors on livelihoods in the Bolivian highlands under a changing climate. *Global Environmental Change*, **22(2)**, 342-352.

McGrath, J. and D.B. Lobell, 2011: An independent method of deriving the carbon dioxide fertilization effect in dry conditions using historical yield data from wet and dry years. *Global Change Biology*, **17(8)**, 2689-2696.

McGuire, A.D., F. Chapin Iii, C. Wirth, M. Apps, J. Bhatti, T. Callaghan, T.R. Christensen, J.S. Clein, M. Fukuda, and T. Maximov, 2007: Responses of high latitude ecosystems to global change: potential consequences for the climate system. In: *Terrestrial Ecosystems in a Changing World* [Canadell, J.G., D.E. Pataki, and L.F. Pitelka (eds.)]. Springer-Verlag, Berlin Heidelberg, pp. 297-310.

McIntyre, T., I.J. Ansorge, H. Bornemann, J. Plötz, C.A. Tosh, and M.N. Bester, 2011: Elephant seal dive behaviour is influenced by ocean temperature. Implications for climate change impacts on an ocean predator. *Marine Ecology Progress Series*, **441**, 257-272.

McKee, K.L., D.R. Cahoon, and I.C. Feller, 2007: Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation. *Global Ecology and Biogeography*, **16(5)**, 545-556.

McLeod, E., R. Moffitt, A. Timmermann, R. Salm, L. Menviel, M.J. Palmer, E.R. Selig, K.S. Casey, and J.F. Bruno, 2010: Warming seas in the Coral Triangle: coral reef vulnerability and management implications. *Coastal Management*, **38(5)**, 518-539.

Menéndez, M. and P.L. Woodworth, 2010: Changes in extreme high water levels based on a quasi-global tide-gauge data set. *Journal of Geophysical Research*, **115(C10)**, C10011, doi:10.1029/2009JC005997.

Menge, B.A., F. Chan, and J. Lubchenco, 2008: Response of a rocky intertidal ecosystem engineer and community dominant to climate change. *Ecology Letters*, **11(2)**, 151-162.

Menne, M.J., C.N. Williams Jr., and R.S. Vose, 2009: The U.S. Historical Climatology Network monthly temperature data, Version 2. *Bulletin of the American Meteorological Society*, **90**, 993-1007.

Menzel, A., T.H. Sparks, N. Estrella, E. Koch, A. Aasa, R. Ahas, K. Alm-Kübler, P. Bissolli, O. Braslavska, A. Briede, F.M. Chmielewski, Z. Crepinsek, Y. Curnel, A. Dahl, C. Defila, A. Donnelly, Y. Filella, K. Jatczak, F. Måge, A. Mestre, Ø. Nordli, J. Peñuelas, P. Pirinen, V. Remišová, H. Scheifinger, M. Striz, A. Susnik, A.J.H. Van Vliet, F.-E. Wielgolaski, S. Zach, and A. Zust, 2006: European phenological response to climate change matches the warming pattern. *Global Change Biology*, **12(10)**, 1969-1976.

Merico, A., T. Tyrrell, E.J. Lessard, T. Oguz, P.J. Stabeno, S.I. Zeeman, and T.E. Whitledge, 2004: Modelling phytoplankton succession on the Bering Sea shelf: role of climate influences and trophic interactions in generating *Emiliania huxleyi* blooms 1997-2000. *Deep-Sea Research Part I*, **51(12)**, 1803-1826.

Miguel, E., S. Satyanath, and E. Sergenti, 2004: Economic shocks and civil conflict: an instrumental variables approach. *Journal of Political Economy*, **112(4)**, 725-753.

Miles, B.W.J., C.R. Stokes, A. Vieli, and N.J. Cox, 2013: Rapid, climate-driven changes in outlet glaciers on the Pacific coast of East Antarctica. *Nature*, **500(7464)**, 563-566.

Miller, S., R. Muir-Wood, and A. Boissonade, 2008: An exploration of trends in normalized weather-related catastrophe losses. In: *Climate Extremes and Society* [Diaz, H.F. and R.J. Murnane (eds.)]. Cambridge University Press, Cambridge, UK, pp. 225-247.

Mills, G., A. Buse, B. Gimeno, V. Bermejo, M. Holland, L. Emberson, and H. Pleijel, 2007: A synthesis of AOT40-based response functions and critical levels of ozone for agricultural and horticultural crops. *Atmospheric Environment*, **41(12)**, 2630-2643.

Min, S.K., X. Zhang, F.W. Zwiers, and G.C. Hegerl, 2011: Human contribution to more-intense precipitation extremes. *Nature*, **470(7334)**, 378-381.

Moholdt, G., B. Wouters, and A.S.S. Gardner, 2012: Recent mass changes of glaciers in the Russian High Arctic. *Geophysical Research Letters*, **39(10)**, L10502, doi:10.1029/2012GL051466.

Moiseev, P.A., A.A. Bartysh, and Z.Y. Nagimov, 2010: Climate changes and tree stand dynamics at the upper limit of their growth in the North Ural Mountains. *Russian Journal of Ecology*, **41(6)**, 486-497.

Molau, U., 2010a: Long-term impacts of observed and induced climate change on tussock tundra near its southern limit in northern Sweden. *Plant Ecology and Diversity*, **3(1)**, 29-34.

Molau, U., 2010b: Recent changes of vegetation patterns in the mountains of northern Sweden. In: *Europe's Ecological Backbone: Recognising the True Value of Mountains*. EEA Report, No. 6/2010, European Environment Agency (EEA), Office for Official Publications of the European Union, Luxembourg, Luxembourg, pp. 159-160.

Mölg, T., N.J. Cullen, D.R. Hardy, G. Kaser, and L. Klok, 2008: Mass balance of a slope glacier on Kilimanjaro and its sensitivity to climate. *International Journal of Climatology*, **28**, 881-892.

Mölg, T., M. Großhauser, A. Hemp, M. Hofer, and B. Marzeion, 2012: Limited forcing of glacier loss through land-cover change on Kilimanjaro. *Nature Climate Change*, **2(4)**, 254-258.

Møller, A.P., D. Rubolini, and E. Lehikoinen, 2008: Populations of migratory bird species that did not show a phenological response to climate change are declining. *Proceedings of the National Academy of Sciences of the United States of America*, **105(42)**, 16195-16200.

Moore, J.A., L.M. Bellchambers, M.R. Depczynski, R.D. Evans, S.N. Evans, S.N. Field, K.J. Friedman, J.P. Gilmour, T.H. Holmes, and R. Middlebrook, 2012: Unprecedented mass bleaching and loss of coral across 12° of latitude in Western Australia in 2010-11. *PloS One*, **7(12)**, e51807, doi:10.1371/journal.pone.0051807.

Moore, R.D., S.W. Fleming, B. Menounos, R. Wheate, A. Fountain, K. Stahl, K. Holm, and M. Jakob, 2009: Glacier change in western North America: influences on hydrology, geomorphic hazards and water quality. *Hydrological Processes*, **23(1)**, 42-61.

Morgan, P.B., T.A. Mies, G.A. Bollero, R.L. Nelson, and S.P. Long, 2006: Season-long elevation of ozone concentration to projected 2050 levels under fully open-air conditions substantially decreases the growth and production of soybean. *New Phytologist*, **170(2)**, 333-343.

Moritz, C., J.L. Patton, C.J. Conroy, J.L. Parra, G.C. White, and S.R. Beissinger, 2008: Impact of a century of climate change on small-mammal communities in Yosemite National Park, USA. *Science*, **322(5899)**, 261-264.

Mote, P.W., 2006: Climate-driven variability and trends in mountain snowpack in western North America. *Journal of Climate*, **19(23)**, 6209-6220.

Moy, A.D., W.R. Howard, S.G. Bray, and T.W. Trull, 2009: Reduced calcification in modern Southern Ocean planktonic foraminifera. *Nature Geoscience*, **2(4)**, 276-280.

Mueter, F.J. and M.A. Litzow, 2008: Sea ice retreat alters the biogeography of the Bering Sea continental shelf. *Ecological Applications*, **18(2)**, 309-320.

Müller, P., 2011: Summer 2010 – wildfires in Russia. In: *Topics Geo. Natural Catastrophes 2010. Analyses, Assessments, Positions.* Munich Reinsurance Company, Munich, Germany, pp. 26-28.

Müller, R., T. Laepple, I. Bartsch, and C. Wiencke, 2009: Impact of oceanic warming on the distribution of seaweeds in polar and cold-temperate waters. *Botanica Marina*, **52(6)**, 617-638.

Muscatine, L., 1986: Bioenergetics of reef-building corals. *Indian Edition Series*, **12**, 297-306.

Myers-Smith, I.H., B.C. Forbes, M. Wilmking, M. Hallinger, T. Lantz, D. Blok, K.D. Tape, M. Macias-Fauria, U. Sass-Klaassen, and E. Lévesque, 2011: Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities. *Environmental Research Letters*, **6(4)**, 045509, doi:10.1088/1748-9326/6/4/045509.

Naito, A.T. and D.M. Cairns, 2011: Patterns and processes of global shrub expansion. *Progress in Physical Geography*, **35(4)**, 423-442.

Nakazawa, Y., R. Williams, A.T. Peterson, P. Mead, E. Staples, and K.L. Gage, 2007: Climate change effects on plague and tularemia in the United States. *Vector-Borne and Zoonotic Diseases*, **7**, 529-540.

Ndebele-Murisa, M.R., E. Mashonjowa, and T. Hill, 2011: The implications of a changing climate on the Kapenta fish stocks of Lake Kariba. *Transactions of the Royal Society of South Africa*, **66**, 105-119.

NDMA, 2011: *National Disaster Management Authority. Annual Report 2010.* National Disaster Management Authority (NDMA), Prime Minister's Secretariat, Islamabad, Pakistan, 78 pp.

Nepstad, D.C. and C.M. Stickler, 2008: Managing the tropical agriculture revolution. *Journal of Sustainable Forestry*, **27(1-2)**, 43-56.

Nepstad, D.C., C.M. Stickler, and O.T. Almeida, 2006: Globalization of the Amazon soy and beef industries: opportunities for conservation. *Conservation Biology*, **20(6)**, 1595-1603.

Neuheimer, A.B., R.E. Thresher, J.M. Lyle, and J.M. Semmens, 2011: Tolerance limit for fish growth exceeded by warming waters. *Nature Climate Change*, **1(2)**, 110-113.

Neumayer, E., 2003: Good policy can lower violent crime: evidence from a cross-national panel of homicide rates, 1980-97. *Journal of Peace Research*, **40(6)**, 619-640.

Neumayer, E. and F. Barthel, 2011: Normalizing economic loss from natural disasters: a global analysis. *Global Environmental Change*, **21(1)**, 13-24.

Nicholls, N., 2006: Detecting and attributing Australian climate change: a review. *Australian Meteorological Magazine*, **55(3)**, 199-211.

Nicholls, N., 2010: Local and remote causes of the southern Australian autumn-winter rainfall decline, 1958-2007. *Climate Dynamics*, **34(6)**, 835-845.

Nicholls, R.J., P.P. Wong, V.R. Burkett, J.O. Codignotto, J.E. Hay, R.F. McLean, S. Ragoonaden, and C.D. Woodroffe, 2007: Coastal systems and low-lying areas. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 315-356.

Nicholls, R.J., C. Woodroffe, and V. Burkett, 2009: Coastline degradation as an indicator of global change. In: *Climate Change: Observed Impacts on Planet Earth* [Letcher, T.M. (ed.)]. Elsevier, Oxford, UK, pp. 409-424.

Nichols, T., F. Berkes, D. Jolly, N.B. Snow, and The Community of Sachs Harbour, 2004: Climate change and sea ice: local observations from the Canadian Western Arctic. *Arctic*, **57(1)**, 68-79.

Nielsen, J.Ø. and A. Reenberg, 2010: Temporality and the problem with singling out climate as a current driver of change in a small West African village. *Journal of Arid Environments*, **74(4)**, 464-474.

Nightingale, A.J., 2011: Bounding difference: intersectionality and the material production of gender, caste, class and environment in Nepal. *Geoforum*, **42(2)**, 153-162.

Novelo-Casanova, D.A. and G. Suarez, 2010: Natural and man-made hazards in the Cayman Islands. *Natural Hazards*, **55(2)**, 441-466.

Nuth, C., G. Moholdt, J. Kohler, J.O. Hagen, and A. Kääb, 2010: Svalbard glacier elevation changes and contribution to sea level rise. *Journal of Geophysical Research: Earth Surface*, **115(F1)**, F01008, doi:10.1029/2008JF001223.

Nye, J.A., J.S. Link, J.A. Hare, and W.J. Overholtz, 2009: Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. *Marine Ecology Progress Series*, **393**, 111-129.

Nye, J.A., T.M. Joyce, Y. Kwon, and J.S. Link, 2011: Silver hake tracks changes in Northwest Atlantic circulation. *Nature Communications*, **2**, 412, doi:10.1038/ncomms1420.

Ogawa-Onishi, Y. and P.M. Berry, 2013: Ecological impacts of climate change in Japan: the importance of integrating local and international publications. *Biological Conservation*, **157**, 361-371.

Ogden, N.H., C. Bouchard, K. Kurtenbach, G. Margos, L.R. Lindsay, L. Trudel, S. Nguon, and F. Milord, 2010: Active and passive surveillance and phylogenetic analysis of *Borrelia burgdorferi* elucidate the process of lyme disease risk emergence in Canada. *Environmental Health Perspectives*, **118(7)**, 909-914.

Okada, M., T. Iizumi, Y. Hayashi, and M. Yokozawa, 2009: A climatological analysis on the recent declining trend of rice quality in Japan. *Journal of Agricultural Meteorology*, **65(4)**, 327-337.

Oliveira, P.J.C., G.P. Asner, D.E. Knapp, A. Almeyda, R. Galvan-Gildemeister, S. Keene, R.F. Raybin, and R.C. Smith, 2007: Land-use allocation protects the Peruvian Amazon. *Science*, **317(5842)**, 1233-1236.

Olsen, M.S., T.V. Callaghan, J.D. Reist, L.O. Reiersen, D. Dahl-Jensen, M.A. Granskog, B. Goodison, G.K. Hovelsrud, M. Johansson, R. Kallenborn, J. Key, A. Klepikov, W. Meier, J.E. Overland, T.D. Prowse, M. Sharp, W.F. Vincent, and J. Walsh, 2011: The changing Arctic cryosphere and likely consequences: an overview. *AMBIO*, **40(1)**, 111-118.

O'Meara, W.P., J. Nekesa Mangeni, R. Steketee, and B. Greenwood, 2010: Changes in the burden of malaria in sub-Saharan Africa. *The Lancet Infectious Diseases*, **10(8)**, 545-555.

Omumbo, J.A., B. Lyon, S.M. Waweru, S.J. Connor, and M.C. Thomson, 2011: Raised temperatures over the Kericho tea estates: revising the climate in the East African highlands malaria debate. *Malaria Journal*, **10(1)**, 12, doi:10.1186/1475-2875-10-12.

Oppikofer, T., M. Jaboyedoff, and H.R. Keusen, 2008: Collapse at the eastern Eiger flank in the Swiss Alps. *Nature Geoscience*, **1(8)**, 531-535.

Osbahr, H., C. Twyman, W. Neil Adger, and D.S.G. Thomas, 2008: Effective livelihood adaptation to climate change disturbance: scale dimensions of practice in Mozambique. *Geoforum*, **39(6)**, 1951-1964.

OSSO, 2013: *La Ruralidad, la Fragilidad Urbana y el Fenómeno La Niña en Colombia, 1971-2011.* Background paper prepared for the Global Assessment Report on Disaster Risk Reduction 2013 by Corporación OSSO, The United Nations Secretariat of the International Strategy for Disaster Reduction (UNISDR), Geneva, Switzerland, 33 pp.

Overeem, I. and J.P.M. Syvitsky, 2010: Shifting discharge peaks in Arctic rivers, 1977-2007. *Geografiska Annaler: Series A, Physical Geography*, **92(2)**, 285-296.

Overland, J.E., J. Alheit, A. Bakun, J.W. Hurrell, D.L. Mackas, and A.J. Miller, 2010: Climate controls on marine ecosystems and fish populations. *Journal of Marine Systems*, **79(3)**, 305-315.

Oxenford, H., R. Roach, A. Brathwaite, L. Nurse, R. Goodridge, F. Hinds, K. Baldwin, and C. Finney, 2008: Quantitative observations of a major coral bleaching event in Barbados, Southeastern Caribbean. *Climatic Change*, **87(3-4)**, 435-449.

Oxley, M., 2011: Field note from Pakistan floods: preventing future flood disasters. *Jàmbá: Journal of Disaster Risk Studies*, **3(2)**, 453-463.

Pall, P., T. Aina, D.A. Stone, P.A. Stott, T. Nozawa, A.G.J. Hilberts, D. Lohmann, and M.R. Allen, 2011: Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature*, **470(7334)**, 382-385.

Panday, P.K. and B. Ghimire, 2012: Time-series analysis of NDVI from AVHRR data over the Hindu Kush-Himalayan region for the period 1982-2006. *International Journal of Remote Sensing*, **33(21)**, 6710-6721.

Parent, M.B. and D. Verbyla, 2010: The browning of Alaska's boreal forest. *Remote Sensing*, **2(12)**, 2729-2747.

Park, S., N. Marshall, E. Jakku, A. Dowd, S. Howden, E. Mendham, and A. Fleming, 2012: Informing adaptation responses to climate change through theories of transformation. *Global Environmental Change*, **22(1)**, 115-126.

Parker, G., 2008: Crisis and catastrophe: the global crisis of the seventeenth century reconsidered. *American Historical Review*, **113(4)**, 1053-1079.

Parmesan, C., 2006: Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics*, **37**, 637-669.

Parmesan, C. and H. Galbraith, 2004: *Observed Impacts of Global Climate Change in the U.S.* Pew Center on Global Climate Change, Arlington, VA, USA, 55 pp.

Parmesan, C. and G. Yohe, 2003: A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, **421(6918)**, 37-42.

Parmesan, C., C.M. Duarte, E. Poloczanska, A.J. Richardson, and M.C. Singer, 2011: Overstretching attribution. *Nature Climate Change*, **1(1)**, 2-4.

Parnikoza, I., P. Convey, I. Dykyy, V. Trokhymets, G. Milinevsky, O. Tyschenko, D. Inozemtseva, and I. Kozeretska, 2009: Current status of the Antarctic herb tundra formation in the Central Argentine Islands. *Global Change Biology*, **15(7)**, 1685-1693.

Parry, M.L., O.F. Canziani, J.P. Palutikof, van der Linden, P J, and C.E. Hanson, 2007: Cross-chapter case study. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 864-868.

Pasquini, A.I. and P.J. Depetris, 2007: Discharge trends and flow dynamics of South American rivers draining the southern Atlantic seaboard: an overview. *Journal of Hydrology*, **333(2)**, 385-399.

Pathak, H., J.K. Ladha, P.K. Aggarwal, S. Peng, S. Das, Y. Singh, B. Singh, S.K. Kamra, B. Mishra, A.S.R.A.S. Sastri, H.P. Aggarwal, D.K. Das, and R.K. Gupta, 2003: Trends of climatic potential and on-farm yields of rice and wheat in the Indo-Gangetic Plains. *Field Crops Research*, **80(3)**, 223-234.

Patterson, D.L., A. Easter-Pilcher, and W.R. Fraser, 2003: The effects of human activity and environmental variability on long-term changes in Adélie penguin populations at Palmer Station, Antarctica. In: *Antarctic Biology in a Global Context* [Huiskes, A., W. Gieskes, J. Rozema, R. Schorno, S. van der Vies, and W. Wolff (eds.)]. Backhuys Publishers, Leiden, Netherlands, pp. 301-307.

Paul, F. and W. Haeberli, 2008: Spatial variability of glacier elevation changes in the Swiss Alps obtained from two digital elevation models. *Geophysical Research Letters*, **35(21)**, L21502, doi:10.1029/2008GL034718.

Paz, S., N. Bisharat, E. Paz, O. Kidar, and D. Cohen, 2007: Climate change and the emergence of *Vibrio vulnificus* disease in Israel. *Environmental Research*, **103(3)**, 390-396.

Pearce, T., B. Smit, F. Duerden, J.D. Ford, A. Goose, and F. Kataoyak, 2010: Inuit vulnerability and adaptive capacity to climate change in Ulukhaktok, Northwest Territories, Canada. *Polar Record*, **46(237)**, 157-177.

Peck, L.S., M.S. Clark, S.A. Morley, A. Massey, and H. Rossetti, 2009: Animal temperature limits and ecological relevance: effects of size, activity and rates of change. *Functional Ecology*, **23(2)**, 248-256.

Pellicciotti, F., A. Bauder, and M. Parola, 2010: Effect of glaciers on streamflow trends in the Swiss Alps. *Water Resources Research*, **46(10)**, W10522, doi:10.1029/2009WR009039.

Peng, C., Z. Ma, X. Lei, Q. Zhu, H. Chen, W. Wang, S. Liu, W. Li, X. Fang, and X. Zhou, 2011: A drought-induced pervasive increase in tree mortality across Canada's boreal forests. *Nature Climate Change*, **1(9)**, 467-471.

Peng, S.B., J.L. Huang, J.E. Sheehy, R.C. Laza, R.M. Visperas, X.H. Zhong, G.S. Centeno, G.S. Khush, and K.G. Cassman, 2004: Rice yields decline with higher night temperature from global warming. *Proceedings of the National Academy of Sciences of the United States of America*, **101(27)**, 9971-9975.

Peñuelas, J., J. Sardans, M. Estiarte, R. Ogaya, J. Carnicer, M. Coll, A. Barbeta, A. Rivas-Ubach, J. Llusià, and M. Garbulsky, 2013: Evidence of current impact of climate change on life: a walk from genes to the biosphere. *Global Change Biology*, **19(8)**, 2303-2388.

Perkins, S.E., L.V. Alexander, and J.R. Nairn, 2012: Increasing frequency, intensity and duration of observed global heatwaves and warm spells. *Geophysical Research Letters*, **39(20)**, L20714, doi:10.1029/2012GL053361.

Perry, A.L., P.J. Low, J.R. Ellis, and J.D. Reynolds, 2005: Climate change and distribution shifts in marine fishes. *Science*, **308(5730)**, 1912-1915.

Perry, C.L. and I.A. Mendelssohn, 2009: Ecosystem effects of expanding populations of *Avicennia germinans* in a Louisiana salt marsh. *Wetlands*, **29(1)**, 396-406.

Peterson, T.C., R.R. Heim Jr., R. Hirsch, D.P. Kaiser, H. Brooks, N.S. Diffenbaugh, R.M. Dole, J.P. Giovannettone, K. Guirguis, T.R. Karl, R.W. Katz, K. Kunkel, D. Lettenmaier, G.J. McCabe, C.J. Paciorek, K.R. Ryberg, S. Schubert, V.B.S. Silva, B.C. Stewart, A.V. Vecchia, G. Villarini, R.S. Vose, J. Walsh, M. Wehner, D. Wolock, K. Wolter, C.A. Woodhouse, and D. Wuebbles, 2013: Monitoring and understanding changes in heat waves, cold waves, flood, and droughts in the United States: state of knowledge. *Bulletin of the American Meteorological Society*, **94(6)**, 821-834.

Petney, T.N., J. Skuballa, S. Muders, M. Pfäffle, C. Zetlmeisl, and R. Oehme, 2012: The changing distribution patterns of ticks (Ixodida) in Europe in relation to emerging tick-borne diseases. *Parasitology Research Monographs*, **3**, 151-166.

Petrow, T. and B. Merz, 2009: Trends in flood magnitude, frequency and seasonality in Germany in the period 1951-2002. *Journal of Hydrology*, **371(1-4)**, 129-141.

Phien-Wej, N., P.H. Giao, and P. Nutalaya, 2006: Land subsidence in Bangkok, Thailand. *Engineering Geology*, **82(4)**, 187-201.

Philippart, C.J.M., R. Anadón, R. Danovaro, J.W. Dippner, K.F. Drinkwater, S.J. Hawkins, T. Oguz, G. O'Sullivan, and P.C. Reid, 2011: Impacts of climate change on European marine ecosystems: observations, expectations and indicators. *Journal of Experimental Marine Biology and Ecology*, **400(1-2)**, 52-69.

Phillimore, A.B., J.D. Hadfield, O.R. Jones, and R.J. Smithers, 2010: Differences in spawning date between populations of common frog reveal local adaptation. *Proceedings of the National Academy of Sciences of the United States of America*, **107(18)**, 8292-8297.

Phillips, O.L., L.E.O.C. Aragão, S.L. Lewis, J.B. Fisher, J. Lloyd, G. López-González, Y. Malhi, A. Monteagudo, J. Peacock, C.A. Quesada, G. van der Heijden, S. Almeida, I. Amaral, L. Arroyo, G. Aymard, T.R. Baker, O. Bánki, L. Blanc, D. Bonal, P. Brando, J. Chave, Á.C. Alves de Oliveira, N.D. Cardozo, C.I. Czimczik, T.R. Feldpausch, M.A. Freitas, E. Gloor, N. Higuchi, E. Jiménez, G. Lloyd, P. Meir, C. Mendoza, A. Morel, D.A. Neill, D. Nepstad, S. Patiño, M.C. Peñuela, A. Prieto, F. Ramírez, M. Schwarz, J. Silva, M. Silveira, A.S. Thomas, H. ter Steege, J. Stropp, R. Vásquez, P. Zelazowski, E.A. Dávila, S. Andelman, A. Andrade, K. Chao, T. Erwin, A. Di Fiore, E. Honorio C., H. Keeling, T.J. Killeen, W.F. Laurance, A.P. Cruz, N.C.A. Pitman, P.N. Vargas, H. Ramírez-Angulo, A. Rudas, R. Salamão, N. Silva, J. Terborgh, and A. Torres-Lezama, 2009: Drought sensitivity of the Amazon rainforest. *Science*, **323(5919)**, 1344-1347.

Pielke Jr., R.A., J. Gratz, C.W. Landsea, D. Collins, M.A. Saunders, and R. Musulin, 2008: Normalised hurricane damage in the United States: 1900-2005. *Natural Hazards Review*, **9**, 29-42.

Pielke Jr., R.A., J. Rubiera, C. Landsea, M.L. Fernandez, and R. Klein, 2003: Hurricane vulnerability in Latin America and the Caribbean: normalized damage and loss potentials. *Natural Hazards Review*, **4(3)**, 101-114.

Pitt, N.R., E.S. Poloczanska, and A.J. Hobday, 2010: Climate-driven range changes in Tasmanian intertidal fauna. *Marine and Freshwater Research*, **61(9)**, 963-970.

Polidoro, B.A., K.E. Carpenter, L. Collins, N.C. Duke, A.M. Ellison, J.C. Ellison, E.J. Farnsworth, E.S. Fernando, K. Kathiresan, N.E. Koedam, S.R. Livingstone, T. Miyagi, G.E. Moore, V.N. Nam, J.E. Ong, J.H. Primavera, S.G. Salmo III, J.C. Sanciangco, S. Sukardjo, Y. Wang, and J.W.H. Yong, 2010: The loss of species: Mangrove extinction risk and geographic areas of global concern. *PLoS ONE*, **5(4)**, e10095, doi:10.1371/journal.pone.0010095.

Poloczanska, E.S., S.J. Hawkins, A.J. Southward, and M.T. Burrows, 2008: Modeling the response of populations of competing species to climate change. *Ecology*, **89(11)**, 3138-3149.

Poloczanska, E.S., S. Smith, L. Fauconnet, J. Healy, I.R. Tibbetts, M.T. Burrows, and A.J. Richardson, 2011: Little change in the distribution of rocky shore faunal communities on the Australian east coast after 50 years of rapid warming. *Journal of Experimental Marine Biology and Ecology*, **400(1-2)**, 145-154.

Poloczanska, E.S., C.J. Brown, W.J. Sydeman, W. Kiessling, D.S. Schoeman, P.J. Moore, K. Brander, J.F. Bruno, L. Buckley, M.T. Burrows, C.M. Duarte, B.S. Halpern, J. Holding, C.V. Kappel, M.I. O'Connor, J.M. Pandolfi, C. Parmesan, F. Schwing, S.A. Thompson, and A.J. Richardson, 2013: Global imprint of climate change on marine life. *Nature Climate Change*, **3(10)**, 919-925.

Porter, J.R. and M. Gawith, 1999: Temperatures and the growth and development of wheat. A review. *European Journal of Agronomy*, **10(1)**, 23-36.

Pörtner, H.O., 2012: Integrating climate-related stressor effects on marine organisms: unifying principles linking molecule to ecosystem-level changes. *Marine Ecology Progress Series*, **470**, 273-290.

Pörtner, H.O. and A.P. Farrell, 2008: Physiology and climate change. *Science*, **322(5902)**, 690-692.

Pörtner, H.O., C. Bock, R. Knust, G. Lannig, M. Lucassen, F.C. Mark, and F.J. Sartoris, 2008: Cod and climate in a latitudinal cline: physiological analyses of climate effects in marine fishes. *Climate Research*, **37(2-3)**, 253-270.

Post, E., M.C. Forchhammer, M.S. Bret-Harte, T.V. Callaghan, T.R. Christensen, B. Elberling, A.D. Fox, O. Gilg, D.S. Hik, T.T. Høye, R.A. Ims, E. Jeppesen, D.R. Klein, J. Madsen, A.D. McGuire, S. Rysgaard, D.E. Schindler, I. Stirling, M.P. Tamstorf, N.J.C. Tyler, R. van der Wal, J. Welker, P.A. Wookey, N.M. Schmidt, and P. Aastrup, 2009: Ecological dynamics across the Arctic associated with recent climate change. *Science*, **325(5946)**, 1355-1358.

Post, V. and E. Abarca, 2010: Preface: saltwater and freshwater interactions in coastal aquifers. *Hydrogeology Journal*, **18(1)**, 1-4.

Pouliotte, J., B. Smit, and L. Westerhoff, 2009: Adaptation and development: livelihoods and climate change in Subarnabad, Bangladesh. *Climate and Development*, **1(1)**, 31-46.

Pounds, J.A., M.R. Bustamante, L.A. Coloma, J.A. Consuegra, M.P.L. Fogden, P.N. Foster, E. La Marca, K.L. Masters, A. Merino-Viteri, R. Puschendorf, S.R. Ron, G.A. Sanchez-Azofeifa, C.J. Still, and B.E. Young, 2006: Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature*, **439(7073)**, 161-167.

Poveda, G. and K. Pineda, 2009: Reassessment of Colombia's tropical glaciers retreat rates: are they bound to disappear during the 2010-2020 decade? *Advances in Geosciences*, **22**, 107-116.

Powers, L.A., T.C. Johnson, J.P. Werne, I.S. Castañeda, E.C. Hopmans, J.S. Sinninghe Damsté, and S. Schouten, 2011: Organic geochemical records of environmental variability in Lake Malawi during the last 700 years, Part I: the TEX_{86} temperature record. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **303(1-4)**, 133-139.

Prathumratana, I., S. Sthiannopkao, and K. Woong Kim, 2008: The relationship of climatic and hydrological parameters to surface water quality in the lower Mekong River. *Environment International*, **34(6)**, 860-866.

Prioux, F., 2005: Recent demographic developments in France. *Population-E*, **60**, 371-414.

Prowse, T.D. and K. Brown, 2010: Appearing and disappearing of lakes in the Arctic and their impacts on biodiversity. In: *Arctic Biodiversity Trends 2010 - Selected Indicators of Change*. Arctic Council, Conservation of Arctic Flora and Fauna Programme (CAFF), CAFF International Secretariat, Akureyri, Iceland, pp. 68-70.

Pulido, F., 2007: Phenotypic changes in spring arrival: evolution, phenotypic plasticity, effects of weather and condition. *Climate Research*, **35**, 5-23.

Quayle, W.C., L.S. Peck, H. Peat, J. Ellis-Evans, and P.R. Harrigan, 2002: Extreme responses to climate change in Antarctic lakes. *Science*, **295(5555)**, 645.

Raabe, E.A., L.C. Roy, and C.C. McIvor, 2012: Tampa Bay coastal wetlands: nineteenth to twentieth century tidal marsh-to-mangrove conversion. *Estuaries and Coasts*, **35(5)**, 1145-1162.

Rabatel, A., B. Francou, A. Soruco, J. Gomez, B. Cáceres, J.L. Ceballos, R. Basantes, M. Vuille, J.E. Sicart, C. Huggel, M. Scheel, Y. Lejeune, Y. Arnaud, M. Collet, T. Condom, G. Consoli, V. Favier, V. Jomelli, R. Galarraga, P. Ginot, L. Maisincho, J. Mendoza, M. Ménégoz, E. Ramirez, P. Ribstein, W. Suarez, M. Villacis, and P. Wagnon, 2013: Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change. *The Cryosphere*, **7**, 81-102.

Rahman, M., T. Lund, and I. Bryceson, 2011: Salinity impacts on agro-biodiversity in three coastal, rural villages of Bangladesh. *Ocean & Coastal Management*, **54(6)**, 455-468.

Raitsos, D.E., G. Beaugrand, D. Georgopoulos, A. Zenetos, A.M. Pancucci-Papadopoulou, A. Theocharis, and E. Papathanassiou, 2010: Global climate change amplifies the entry of tropical species into the Eastern Mediterranean Sea. *Limnology and Oceanography*, **55(4)**, 1478-1484.

Rajeevan, M., A.K. Srivastava, Z. Lareef, and J. Revadekar, 2011: South Asia. In: *State of the Climate in 2010* [Blunden, J., D.S. Arndt, and M.O. Baringer (eds.)]. Special Supplement to the *Bulletin of the American Meteorological Society*, **92(6)**, S217-S219.

Raleigh, C. and D. Kniveton, 2012: Come rain or shine: an analysis of conflict and climate variability in East Africa. *Journal of Peace Research*, **49**, 51-64.

Ranasinghe, R. and M.J.F. Stive, 2009: Rising seas and retreating coastlines. *Climatic Change*, **97(3)**, 465-468.

Randolph, S.E. and D.J. Rogers, 2010: The arrival, establishment and spread of exotic diseases: patterns and predictions. **8(5)**, 361-371.

Rankey, E.C., 2011: Nature and stability of atoll island shorelines: Gilbert Island chain, Kiribati, equatorial Pacific. *Sedimentology*, **58(7)**, 1831-1859.

Rasheed, M.A. and R.K.F. Unsworth, 2011: Long-term climate-associated dynamics of a tropical seagrass meadow. Implications for the future. *Marine Ecology Progress Series*, **422**, 93-103.

Raupach, M.R., J.G. Canadell, and C. Le Quéré, 2008: Anthropogenic and biophysical contributions to increasing atmospheric CO_2 growth rate and airborne fraction. *Biogeosciences*, **5**, 1601-1613.

Ravanel, L. and P. Deline, 2011: Climate influence on rockfalls in high-Alpine steep rockwalls. The north side of the Aiguilles de Chamonix (Mont Blanc massif) since the end of the 'Little Ice Age'. *The Holocene*, **21(2)**, 357-365.

Ravens, T.M., R.C. Thomas, K.A. Roberts, and P.H. Santschi, 2009: Causes of salt marsh erosion in Galveston Bay, Texas. *Journal of Coastal Research*, **25(2)**, 265-272.

Raxworthy, C.J., R.G. Pearson, N. Rabibisoa, A.M. Rakotondrazafy, J.B. Ramanamanjato, A.P. Raselimanana, S. Wu, R.A. Nussbaum, and D.A. Stone, 2008: Extinction vulnerability of tropical montane endemism from warming and upslope displacement: a preliminary appraisal for the highest massif in Madagascar. *Global Change Biology*, **14(8)**, 1703-1720.

Razumov, S.O., 2010: Permafrost as a factor of the dynamics of the coastal zone of the Russian East Arctic Seas. *Oceanology*, **50(2)**, 262-267.

Resurreccion, B.P., 2011: *The Gender and Climate Debate. More of the Same or New Pathways of Thinking and Doing?* Asia Security Initiative Policy Series Working Paper No.10, RSIS Center for Non-Traditional Security Studies, Singapore, 19 pp.

Reusch, T.B., A. Ehlers, A. Hammerli, and B. Worm, 2005: Ecosystem recovery after climatic extremes enhanced by genotypic diversity. *Proceedings of the National Academy of Sciences of the United States of America*, **102(8)**, 2826-2831.

Rey, G., E. Jougla, A. Fouillet, G. Pavillon, P. Bessemoulin, P. Frayssinet, J. Clavel, and D. Hémon, 2007: The impact of major heat waves on all-cause and cause-specific mortality in France from 1971 to 2003. *International Archives of Occupational and Environmental Health*, **80**, 615-626.

Richardson, A.J., C.J. Brown, K. Brander, J.F. Bruno, L. Buckley, M.T. Burrows, C.M. Duarte, B.S. Halpern, O. Hoegh-Guldberg, J. Holding, C.V. Kappel, W. Kiessling, P.J. Moore, M.I. O'Connor, J.M. Pandolfi, C. Parmesan, D.S. Schoeman, F. Schwing, W.J. Sydeman, and E.S. Poloczanska, 2012: Climate change and marine life. *Biology Letters*, **8(6)**, 907-909.

Riordan, B., D. Verbyla, and D.A. McGuire, 2006: Shrinking ponds in subarctic Alaska based on 1950-2002 remotely sensed images. *Journal of Geophysical Research*, **111(G4)**, G02004, doi:10.1029/2005JG000150.

Rivadeneira, M.M. and M. Fernández, 2005: Shifts in southern endpoints of distribution in rocky intertidal species along the south-eastern Pacific coast. *Journal of Biogeography*, **32(2)**, 203-209.

Robards, M., 2013: Resilience of international policies to changing social-ecological systems: Arctic shipping in the Bering Strait. In: *Arctic Resilience Interim Report.* Arctic Council, Stockholm Environment Institute (SEI) and Stockholm Resilience Centre, Stockholm, Sweden, pp. 99-104.

Rocklöv, J., B. Forsberg, and K. Meister, 2009: Winter mortality modifies the heat-mortality association the following summer. *European Respiratory Journal*, **33(2)**, 245-251.

Rodell, M., I. Velicogna, and J.S. Famiglietti, 2009: Satellite-based estimates of groundwater depletion in India. *Nature*, **460(7258)**, 999-1002.

Rodriguez-Oreggia, E., A. De La Fuente, R. De La Torre, and H.A. Moreno, 2013: Natural disasters, human development and poverty at the municipal level in Mexico. *The Journal of Development Studies*, **49(3)**, 442-455.

Roessig, J.M., C.M. Woodley, J.J. Cech, and L.J. Hansen, 2004: Effects of global climate change on marine and estuarine fishes and fisheries. *Reviews in Fish Biology and Fisheries*, **14**, 251-275.

Romanovsky, V.E., D.S. Drozdov, N.G. Oberman, G.V. Malkova, A.L. Kholodov, S.S. Marchenko, N.G. Moskalenko, D.O. Sergeev, N.G. Ukraintseva, A.A. Abramov, D.A. Gilichinsky, and A.A. Vasiliev, 2010: Thermal state of permafrost in Russia. *Permafrost and Periglacial Processes*, **21(2)**, 136-155.

Romine, B.M., C.H. Fletcher, M.M. Barbee, T.R. Anderson, and L.N. Frazer, 2013: Are beach erosion rates and sea-level rise related in Hawaii? *Global and Planetary Change*, **108(9)**, 149-157.

Root, T.L., D.P. MacMynowski, M.D. Mastrandrea, and S.H. Schneider, 2005: Human-modified temperatures induce species changes: joint attribution. *Proceedings of the National Academy of Sciences of the United States of America*, **102(21)**, 7465-7469.

Rosenzweig, C. and P. Neofotis, 2013: Detection and attribution of anthropogenic climate change impacts. *Wiley Interdisciplinary Reviews: Climate Change*, **4(2)**, 121-150.

Rosenzweig, C., F.N. Tubiello, R. Goldberg, E. Mills, and J. Bloomfield, 2002: Increased crop damage in the US from excess precipitation under climate change. *Global Environmental Change*, **12(3)**, 197-202.

Rosenzweig, C., G. Casassa, D.J. Karoly, A. Imeson, C. Liu, A. Menzel, S. Rawlins, T.L. Root, B. Seguin, and P. Tryjanowski, 2007: Assessment of observed changes and responses in natural and managed systems. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, van der Linden, P. J., and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, U.K and New York, NY, USA, pp. 79-131.

Rosenzweig, C., D. Karoly, M. Vicarelli, P. Neofotis, Q. Wu, G. Casassa, A. Menzel, T.L. Root, N. Estrella, B. Seguin, P. Tryjanowski, C. Liu, S. Rawlins, and A. Imeson, 2008: Attributing physical and biological impacts to anthropogenic climate change. *Nature*, **453(7193)**, 353-357.

Ross, M.S., J.J. O'Brien, R.G. Ford, K. Zhang, and A. Morkill, 2009: Disturbance and the rising tide: the challenge of biodiversity management on low-island ecosystems. *Frontiers in Ecology and the Environment*, **7(9)**, 471-478.

Rothstein, H.R., A.J. Sutton, and M. Borenstein (eds.), 2005: *Publication Bias in Meta-Analysis: Prevention, Assessment, and Adjustments*. John Wiley & Sons, Chichester, UK, 374 pp.

Rotton, J. and E.G. Cohn, 2001: Temperature, routine activities, and domestic violence: a reanalysis. *Violence and Victims*, **16(2)**, 203-215.

Rowland, J.C., C.E. Jones, G. Altmann, R. Bryan, B.T. Crosby, G.L. Geernaert, L.D. Hinzman, L.D. Kane, D.M. Lawrence, A. Mancino, P. Marsh, J.P. McNamara, V.E. Romanovsky, H. Toniolo, B.J. Travis, E. Trochim, and C.J. Wilson, 2010: Arctic landscapes in transition: responses to thawing permafrost. *Eos, Transactions of the American Geophysical Union*, **91(26)**, 229-236.

Rozell, D.J. and T.F. Wong, 2010: Effects of climate change on groundwater resources at Shelter Island, New York State, USA. *Hydrogeology Journal*, **18(7)**, 1657-1665.

Rubidge, E.M., W.B. Monahan, J.L. Parra, S.E. Cameron, and J.S. Brashares, 2011: The role of climate, habitat, and species co-occurrence as drivers of change in small mammal distributions over the past century. *Global Change Biology*, **17(2)**, 696-708.

Ruiz-Labourdette, D., M.F. Schmitz, and F.D. Pineda, 2013: Changes in tree species composition in Mediterranean Mountains under climate change: indicators for conservation planning. *Ecological Indicators*, **24**, 310-323.

Saba, V.S., M.A.M. Friedrichs, M.E. Carr, D. Antoine, R.A. Armstrong, I. Asanuma, O. Aumont, N.R. Bates, M.J. Behrenfeld, V. Bennington, L. Bopp, J. Bruggeman, E.T. Buitenhuis, M.J. Church, A.M. Ciotti, S.C. Doney, M. Dowell, J. Dunne, S. Dutkiewicz, W. Gregg, N. Hoepffner, K.J.W. Hyde, J. Ishizaka, T. Kameda, D.M. Karl, I. Lima, M.W. Lomas, J. Marra, G.A. McKinley, F. Melin, J.K. Moore, A. Morel, J. O'Reilly, B. Salihoglu, M. Scardi, T.J. Smyth, S.L. Tang, J. Tjiputra, J. Uitz, M. Vichi, K. Waters, T.K. Westberry, and A. Yool, 2010: Challenges of modeling depth-integrated marine primary productivity over multiple decades: a case study at BATS and HOT. *Global Biogeochemical Cycles*, **24(3)**, GB3020, doi:10.1029/2009GB003655.

Saldaña-Zorrilla, S. and K. Sandberg, 2009: Impact of climate-related disasters on human migration in Mexico: a spatial model. *Climatic Change*, **96(1-2)**, 97-118.

Salick, J. and N. Ross, 2009: Traditional peoples and climate change: introduction. *Global Environmental Change*, **19(2)**, 137-139.

Sander, J., J.F. Eichner, E. Faust, and M. Steuer, 2013: Rising variability in thunderstorm-related U.S. losses as a reflection of changes in large-scale thunderstorm forcing. *Journal of the American Meteorological Society*, **5(4)**, 317-331.

Sandin, S.A., J.E. Smith, E.E. DeMartini, E.A. Dinsdale, S.D. Donner, A.M. Friedlander, T. Konotchick, M. Malay, J.E. Maragos, and D. Obura, 2008: Baselines and degradation of coral reefs in the northern Line Islands. *PLoS ONE*, **3(2)**, e1548, doi:10.1371/journal.pone.0001548.

Sato, Y., D.G. Bourne, and B.L. Willis, 2009: Dynamics of seasonal outbreaks of black band disease in an assemblage of Montipora species at Pelorus Island (Great Barrier Reef, Australia). *Proceedings of the Royal Society B*, **276(1668)**, 2795-2803.

Saurral, R.I., V.R. Barros, and D.P. Lettenmaier, 2008: Land use impact on the Uruguay River discharge. *Geophysical Research Letters*, **35(12)**, L12401, doi:10.1029/2008GL033707.

Schlenker, W. and M.J. Roberts, 2009: Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **106(37)**, 15594-15598.

Schlenker, W., W.M. Hanemann, and A.C. Fisher, 2005: Will U.S. agriculture really benefit from global warming? Acounting for irrigation in the hedonic approach. *The American Economic Review*, **95(1)**, 395-406.

Schleupner, C., 2008: Evaluation of coastal squeeze and its consequences for the Caribbean island Martinique. *Ocean & Coastal Management*, **51(5)**, 383-390.

Schmidt, S., C. Kemfert, and P. Höppe, 2010: The impact of socio-economics and climate change on tropical cyclone losses in the USA. *Regional Environmental Change*, **10(1)**, 13-26.

Schmocker-Fackel, P. and F. Naef, 2010: More frequent flooding? Changes in flood frequency in Switzerland since 1850. *Journal of Hydrology*, **381(1)**, 1-8.

Schneider, D., C. Huggel, W. Haeberli, and R. Kaitna, 2011: Unraveling driving factors for large rock-ice avalanche mobility. *Earth Surface Processes and Landforms*, **36(14)**, 1948-1966.

Schneider, P. and S.J. Hook, 2010: Space observations of inland water bodies show rapid surface warming since 1985. *Geophysical Research Letters*, **37(22)**, L22405, doi:10.1029/2010GL045059.

Schwing, F.B., R. Mendelssohn, S.J. Bograd, J.E. Overland, M. Wang, and S. Ito, 2010: Climate change, teleconnection patterns, and regional processes forcing marine populations in the Pacific. *Journal of Marine Systems*, **79(3)**, 245-257.

Scott, D., B. Amelung, S. Becken, J.P. Ceron, G. Dubois, S. Gössling, P. Peeters, and M.C. Simpson, 2008: *Climate Change and Tourism: Responding to Global Challenges.* Report coordinated by UNWTO, UNEP, and WMO, Published by the World Tourism Organization (UNWTO), Madrid, Spain and the United Nations Environment Programme (UNEP), Paris, France, 256 pp.

Senapathi, D., M.A.C. Nicoll, C. Teplitsky, C.G. Jones, and K. Norris, 2011: Climate change and the risks associated with delayed breeding in a tropical wild bird population. *Proceedings of the Royal Society B*, **278(1722)**, 3184-3190.

Seneviratne, S.I., N. Nicholls, D. Easterling, C.M. Goodess, S. Kanae, J. Kossin, Y. Luo, J. Marengo, K. McInnes, M. Rahimi, M. Reichstein, A. Sorteberg, C. Vera, and X. Zhang, 2012: Changes in climate extremes and their impacts on the natural physical environment. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 109-230.

Sheffield, J. and E.F. Wood, 2007: Characteristics of global and regional drought, 1950-2000: analysis of soil moisture data from off-line simulation of the terrestrial hydrologic cycle. *Journal of Geophysical Research: Atmospheres (1984–2012)*, **112(D17)**, D17115, doi:10.1029/2006JD008288.

Sheppard, C., M. Al-Husiani, F. Al-Jamali, F. Al-Yamani, R. Baldwin, J. Bishop, F. Benzoni, E. Dutrieux, N.K. Dulvy, S.R. Durvasula, D.A. Jones, R. Loughland, D. Medio, M. Nithyanandan, G.M. Pilling, I. Polikarpov, A.R. Price, S. Purkis, B. Riegl, M. Saburova, K.S. Namin, O. Taylor, S. Wilson, and K. Zainal, 2010: The Gulf: a young sea in decline. *Marine Pollution Bulletin*, **60(1)**, 13-38.

Shiklomanov, A.I., R.B. Lammers, M.A. Rawlins, L.C. Smith, and T.M. Pavelsky, 2007: Temporal and spatial variations in maximum river discharge from a new Russian data set. *Journal of Geophysical Research*, **112**, G04S53, doi:10.1029/2006JG000352.

Shrestha, U.B., S. Gautam, and K.S. Bawa, 2012: Widespread climate change in the Himalayas and associated changes in local ecosystems. *PLoS ONE*, **7(5)**, e36741, doi:10.1371/journal.pone.0036741.

Shriver, A.L., B.H. Yeo, K.O. Ting, M. Garcia, and M. Ahmed (eds.), 2006: Annotated bibliography on the economic effects of global climate change on fisheries. Prepared by the Information and Knowledge Group, World Fish Center for the Consultation on the Impact of Global Climate Change on Aquatic Resources, Food, and Income Security of Fishing-dependent Populations, San Diego, CA, USA, 24-25 August 2005, World Fish Center, Penang, Malaysia, 46 pp.

Simmons, K., D. Sutter, and R.A. Pielke Jr, 2013: Normalized tornado damage in the United States: 1950-2011. *Environmental Hazards*, **12(2)**, 132-147.

Slettebak, R.T., 2012: Don't blame the weather! Climate-related natural disasters and civil conflict. *Journal of Peace Research*, **49(1)**, 163-176.

Smith, J.B., J. Schellnhuber, M. Mirza, S. Fankhauser, R. Leemans, L. Erda, L. Ogallo, B. Pittock, R. Richels, C. Rosenzweig, U. Safriel, R.S.J. Tol, J. Weyant, and G. Yohe, 2001: Vulnerability to climate change and reasons for concern: a synthesis. In: *Climate Change 2001: Impacts, Adaptation and Vulnerability . Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 913-967.

Smith, J.B., S.H. Schneider, M. Oppenheimer, G.W. Yohe, W. Hare, M.D. Mastrandrea, A. Patwardhan, I. Burton, J. Corfee-Morlot, C.H.D. Magadza, H.M. Füssel, A.B. Pittock, A. Rahman, A. Suarez, and J.P. Van Ypersele, 2009: Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) 'Reasons for concern'. *Proceedings of the National Academy of Sciences of the United States of America*, **106(11)**, 4133-4137.

Smith, J.R., P. Fong, and R.F. Ambrose, 2006: Dramatic declines in mussel bed community diversity: response to climate change? *Ecology*, **87(5)**, 1153-1161.

Soja, A., N.M. Tchebakova, N.H.F. French, M.D. Flannigan, H.M. Shugart, B.J. Stocks, A.I. Sukhinin, E.I. Parfenova, Chapin III, F.S., and P.W. Stockhouse Jr., 2007: Climate-induced boreal forest change predictions vs. current observations. *Global Planetary Change*, **56**, 274-296.

Somero, G.N., 2012: The physiology of global change: linking patterns to mechanisms. *Annual Review of Marine Science*, **4**, 39-61.

Stahl, K., H. Hisdal, J. Hannaford, L. Tallaksen, H. Van Lanen, E. Sauquet, S. Demuth, M. Fendekova, and J. Jordar, 2010: Streamflow trends in Europe: evidence from a dataset of near-natural catchments. *Hydrology and Earth System Sciences Discussions*, **14**, 2367-2382.

Stern, D.I., P.W. Gething, C.W. Kabaria, W.H. Temperley, A.M. Noor, E.A. Okiro, G.D. Shanks, R.W. Snow, and S.I. Hay, 2011: Temperature and malaria trends in highland East Africa. *PLoS ONE*, **6(9)**, e24524, doi:10.1371/journal.pone.0024524.

Stewart, I.T., D.R. Cayan, and M.D. Dettinger, 2005: Changes toward earlier streamflow timing across western North America. *Journal of Climate*, **18(8)**, 1136-1151.

Stige, L.C., G. Ottersen, K. Brander, K.S. Chan, and N.C. Stenseth, 2006: Cod and climate. Effect of the North Atlantic Oscillation on recruitment in the North Atlantic. *Marine Ecology Progress Series*, **325**, 227-241.

Stige, L.C., G. Ottersen, P. Dalpadado, K.S. Chan, D. Hjermann, D.L. Lajus, N.A. Yaragina, and N.C. Stenseth, 2010: Direct and indirect climate forcing in a multi-species marine system. *Proceedings of the Royal Society B*, **277(1699)**, 3411-3420.

Stinson, G., W. Kurz, C. Smyth, E. Neilson, C. Dymond, J. Metsaranta, C. Boisvenue, G. Rampley, Q. Li, and T. White, 2011: An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. *Global Change Biology*, **17(6)**, 2227-2244.

Stock, C.A., M.A. Alexander, N.A. Bond, K.M. Brander, W.W.L. Cheung, E.N. Curchitser, T.L. Delworth, J.P. Dunne, S.M. Griffies, M.A. Haltuch, J.A. Hare, A.B. Hollowed, P. Lehodey, S.A. Levin, J.S. Link, K.A. Rose, R.R. Rykaczewski, J.L. Sarmiento, R.J. Stouffer, F.B. Schwing, G.A. Vecchi, and F.E. Werner, 2010: On the use of IPCC-class models to assess the impact of climate on Living Marine Resources. *Progress in Oceanography*, **88(1)**, 1-27.

Stoffel, M. and C. Huggel, 2012: Effects of climate change on mass movements in mountain environments. *Progress in Physical Geography*, **36(6)**, 421-439.

Stokes, C.R., M. Shahgedanova, I.S. Evans, and V.V. Popovnin, 2013: Accelerated loss of alpine glaciers in the Kodar Mountains, south-eastern Siberia. *Global and Planetary Change*, **101(2)**, 82-96.

Stokes, D.J., T.R. Healy, and P.J. Cooke, 2010: Expansion dynamics of monospecific, temperate mangroves and sedimentation in two embayments of a barrier-enclosed lagoon, Tauranga Harbour, New Zealand. *Journal of Coastal Research*, **26(1)**, 113-122.

Stolper, D.A., N.P. Revsbech, and D.E. Canfield, 2010: Aerobic growth at nanomolar oxygen concentrations. *Proceedings of the National Academy of Sciences of the United States of America*, **107(44)**, 18755-18760.

Stone, D., M. Auffhammer, M. Carey, G. Hansen, C. Huggel, W. Cramer, D. Lobell, U. Molau, A. Solow, L. Tibig, and G. Yohe, 2013: The challenge to detect and attribute effects of climate change on human and natural systems. *Climatic Change*, **121(2)**, 381-395.

Storey, D. and S. Hunter, 2010: Kiribati: an environmental 'perfect storm'. *Australian Geographer*, **41(2)**, 167-181.

Stramma, L., G.C. Johnson, J. Sprintall, and V. Mohrholz, 2008: Expanding oxygen-minimum zones in the tropical oceans. *Science*, **320(5876)**, 655-658.

Stramma, L., S. Schmidtko, L.A. Levin, and G.C. Johnson, 2010: Ocean oxygen minima expansions and their biological impacts. *Deep-Sea Research Part I: Oceanographic Research Papers*, **57(4)**, 587-595.

Stramma, L., E.D. Prince, S. Schmidtko, J. Luo, J.P. Hoolihan, M. Visbeck, D.W.R. Wallace, P. Brandt, and A. Kortzinger, 2012: Expansion of oxygen minimum zones may reduce available habitat for tropical pelagic fishes. *Nature Climate Change*, **2(1)**, 33-37.

Strong, A.E., G. Liu, W. Skirving, and C.M. Eakin, 2011: NOAA's Coral Reef Watch program from satellite observations. *Annals of GIS*, **17(2)**, 83-92.

Šumilo, D., A. Bormane, L. Asokliene, V. Vasilenko, I. Golovljova, T. Avsic-Zupanc, Z. Hubalek, and S.E. Randolph, 2008: Socio-economic factors in the differential upsurge of tick-borne encephalitis in Central and Eastern Europe. *Reviews in Medical Virology*, **18(2)**, 81-95.

Šumilo, D., A. Bormane, V. Vasilenko, I. Golovljova, L. Asokliene, M. Žygutiene, and S. Randolph, 2009: Upsurge of tick-borne encephalitis in the Baltic States at the time of political transition, independent of changes in public health practices. *Clinical Microbiology and Infection*, **15(1)**, 75-80.

Sunday, J.M., A.E. Bates, and N.K. Dulvy, 2012: Thermal tolerance and the global redistribution of animals. *Nature Climate Change*, **2(9)**, 686-690.

Supit, I., C.A. van Diepen, A.J.W. de Wit, P. Kabat, B. Baruth, and F. Ludwig, 2010: Recent changes in the climatic yield potential of various crops in Europe. *Agricultural Systems*, **103**, 683-694.

Svensson, C., J. Hannaford, Z.W. Kundzewicz, and T.J. Marsh, 2006: Trends in river floods: why is there no clear signal in observations? *IAHS Publications-Series of Proceedings and Reports*, **305**, 1-18.

Sydeman, W.J. and S.J. Bograd, 2009: Marine ecosystems, climate, and phenology: introduction. *Marine Ecology Progress Series*, **393**, 185-188.

Syvitski, J.P.M., C.J. Vörösmarty, A.J. Kettner, and P. Green, 2005: Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science*, **308(5720)**, 376-380.

Takasuka, A., Y. Oozeki, and I. Aoki, 2007: Optimal growth temperature hypothesis. Why do anchovy flourish and sardine collapse or vice versa under the same ocean regime? *Canadian Journal of Fisheries and Aquatic Sciences*, **64(5)**, 768-776.

Takasuka, A., Y. Oozeki, and H. Kubota, 2008: Multi-species regime shifts reflected in spawning temperature optima of small pelagic fish in the western North Pacific. *Marine Ecology Progress Series*, **360**, 211-217.

Tamisiea, M.E. and J.X. Mitrovica, 2011: The moving boundaries of sea level change: understanding the origins of geographic variability. *Oceanography*, **24**, 24-39.

Tan, A., J.C. Adam, and D.P. Lettenmaier, 2011: Change in spring snowmelt timing in Eurasian Arctic rivers. *Journal of Geophysical Research*, **116(D3)**, D03101, doi:10.1029/2010JD014337.

Tao, F., M. Yokozawa, Y. Xu, Y. Hayashi, and Z. Zhang, 2006: Climate changes and trends in phenology and yields of field crops in China, 1981-2000. *Agricultural and Forest Meteorology*, **138(1)**, 82-92.

Tao, F., M. Yokozawa, J. Liu, and Z. Zhang, 2008: Climate-crop yield relationships at provincial scales in China and the impacts of recent climate trends. *Climate Research*, **38(1)**, 83-94.

Tao, F., Z. Zhang, S. Zhang, Z. Zhu, and W. Shi, 2012: Response of crop yields to climate trends since 1980 in China. *Climate Research*, **54**, 233-247.

Tape, K.D., M. Sturm, and C. Racine, 2006: The evidence for shrub expansion in northern Alaska and the Pan-Arctic. *Global Change Biology*, **12(4)**, 686-702.

Tape, K.D., M. Hallinger, J.M. Welker, and R.W. Ruess, 2012: Landscape heterogeneity of shrub expansion in arctic Alaska. *Ecosystems*, **15(5)**, 1-14.

Tasker, M.L., 2008: *The Effect of Climate Change on the Distribution and Abundance of Marine Species in the OSPAR Maritime Area.* ICES Cooperative Research Report No. 293, International Council for the Exploration of the Sea (ICES), Copenhagen, Denmark, 45 pp.

Taylor, R.G., L. Mileham, C. Tindimugaya, and L. Mwebembezi, 2009: Recent glacial recession and its impact on alpine riverflow in the Rwenzori Mountains of Uganda. *Journal of African Earth Sciences*, **55(3-4)**, 205-213.

Taylor, R.G., B. Scanlon, P. Doll, M. Rodell, R. Van Beek, Y. Wada, L. Longuevergne, M. Leblanc, J.S. Famiglietti, M. Edmunds, L. Konikow, T.R. Green, J. Chen, M. Taniguchi, M.F.P. Bierkens, A. MacDonald, Y. Fan, R.M. Maxwell, Y. Yechieli, J.J. Gurdak, D.M. Allen, M. Shamsudduha, K. Hiscock, P.J.F. Yeh, I. Holman, and H. Treidel, 2013: Ground water and climate change. *Nature Climate Change*, **3(4)**, 322-329.

Terrier, S., F. Jordan, A. Schleiss, W. Haeberli, C. Huggel, and M. Künzler, 2011: Optimized and adaptated hydropower management considering glacier shrinkage in the Swiss Alps. In: *Dams and Reservoirs under Changing Challenges* [Schleiss, A. and R.M. Boes (eds.)]. Proceedings of the International Symposium on Dams and Reservoirs under Changing Challenges: 79th Annual Meeting of ICOLD, Swiss Committee on Dams, Lucerne, Switzerland, 1 June, 2011, CRC Press, Taylor & Francis Group, London, UK, pp. 497-508.

Terry, J.P. and A.C. Falkland, 2010: Responses of atoll freshwater lenses to storm-surge overwash in the Northern Cook Islands. *Hydrogeology Journal*, **18(3)**, 749-759.

Thaxter, C.B., A.C. Joys, R.D. Gregory, S.R. Baillie, and D.G. Noble, 2010: Hypotheses to explain patterns of population change among breeding bird species in England. *Biological Conservation*, **143(9)**, 2006-2019.

Theisen, O.M., 2012: Climate clashes? Weather variability, land pressure, and organized violence in Kenya, 1989-2004. *Journal of Peace Research*, **49(1)**, 81-96.

Theisen, O.M., H. Holtermann, and H. Buhaug, 2011: Climate wars? Assessing the claim that drought breeds conflict. *International Security*, **36(3)**, 79-106.

Thiaw, W.M., A.C. Kruger, D.M. Patricio, L. Njau, M. Kadi, and S. Tinni, 2008: Southern Africa. In: *State of the Climate in* 2007 [Levinson, D.H. and J.H. Lawrimore (eds.)]. Special Supplement to the *Bulletin of the American Meteorological Society*, **89(7)**, S109-S111.

Thomas, D.S.G., C. Twyman, H. Osbahr, N. Adger, and B. Hewitson, 2007: Adaptation to climate change and variability: farmer responses to intra-seasonal precipitation trends in South Africa. *Climatic Change*, **83(3)**, 301-322.

Thorburn, P.J., M.J. Robertson, B.E. Clothier, V.O. Snow, E. Charmley, J. Sanderman, E. Teixeira, R.A. Dynes, A. Hall, H. Brown, S.M. Howden, and M. Battaglia, 2012: Australia and New Zealand perspectives on climate change and agriculture. In: *Handbook of Climate Change and Agroecosystems: Global and Regional Aspects and Implications* [Rosenzweig, C. and D. Hillel (eds.)]. American Society of Agronomy and Imperial College Press, New York, NY, USA, pp. 107-142.

Tian, Y., H. Kidokoro, T. Watanabe, Y. Igeta, H. Sakaji, and S. Ino, 2012: Response of yellowtail, *Seriola quinqueradiata*, a key large predatory fish in the Japan Sea, to sea water temperature over the last century and potential effects of global warming. *Journal of Marine Systems*, **91(1)**, 1-10.

Tierney, J.E., M.T. Mayes, N. Meyer, C. Johnson, P.W. Swarzenski, A.S. Cohen, and J.M. Russell, 2010: Late-twentieth-century warming in Lake Tanganyika unprecedented since AD 500. *Nature Geoscience*, **3**, 422-425.

Tingley, M.W., W.B. Monahan, S.R. Beissinger, and C. Moritz, 2009: Birds track their Grinnellian niche through a century of climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **106(Suppl. 2)**, 19637-19643.

Tingley, M.W., M.S. Koo, C. Moritz, A.C. Rush, and S.R. Beissinger, 2012: The push and pull of climate change causes heterogeneous shifts in avian elevational ranges. *Global Change Biology*, **18(11)**, 3279-3290.

Tol, R.S.J. and S. Wagner, 2010: Climate change and violent conflict in Europe over the last millennium. *Climatic Change*, **99(1-2)**, 65-79.

Toniolo, H., P. Kodial, L.D. Hinzman, and K. Yoshikawa, 2009: Spatio-temporal evolution of a thermokarst in Interior Alaska. *Cold Regions Science and Technology*, **56(1)**, 39-49.

Trathan, P.N., P.T. Fretwell, and B. Stonehouse, 2011: First recorded loss of an emperor penguin colony in the recent period of Antarctic regional warming: implications for other colonies. *PLoS ONE*, **6(2)**, e14738, doi:10.1371/journal.pone.0014738.

Trenberth, K.E., 2011: Attribution of climate variations and trends to human influences and natural variability. *Wiley Interdisciplinary Reviews: Climate Change*, **2(6)**, 925-930.

Trivelpiece, W.Z., J.T. Hinke, A.K. Miller, C.S. Reiss, S.G. Trivelpiece, and G.M. Watters, 2011: Variability in krill biomass links harvesting and climate warming to penguin population changes in Antarctica. *Proceedings of the National Academy of Sciences of the United States of America*, **108(18)**, 7625-7628.

Tschakert, P., R. Tutu, and A. Alcaro, 2013: Embodied experiences of environmental and climatic changes in landscapes of everyday life in Ghana. *Emotion, Space and Society*, **7(May 2013)**, 13-25.

Turetsky, M.R., E.S. Kane, J.W. Harden, R.D. Ottmar, K.L. Manies, E. Hoy, and E.S. Kasischke, 2010: Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands. *Nature Geoscience*, **4(1)**, 27-31.

Uhlmann, M., O. Korup, C. Huggel, L. Fischer, and J.S. Kargel, 2013: Supra-glacial deposition and flux of catastrophic rock-slope failure debris, south-central Alaska. *Earth Surface Processes and Landforms*, **38(6)**, 675-682.

Vadadi-Fülöp, C., C. Sipkay, G. Mészáros, and L. Hufnagel, 2012: Climate change and freshwater zooplankton: what does it boil down to? *Aquatic Ecology*, **46(4)**, 501-519.

Valt, M. and P. Cianfarra, 2010: Recent snow cover variability in the Italian Alps. *Cold Regions Science and Technology*, **64(2)**, 146-157.

Van Bogaert, R., K. Haneca, J. Hoogesteger, C. Jonasson, M. De Dapper, and T.V. Callaghan, 2011: A century of tree line changes in sub-Arctic Sweden shows local and regional variability and only a minor influence of 20th century climate warming. *Journal of Biogeography*, **38(5)**, 907-921.

Van den Honert, R.C. and J. McAneney, 2011: The 2011 Brisbane floods: causes, impacts and implications. *Water*, **3(4)**, 1149-1173.

Van Dijk, J., N.D. Sargison, F. Kenyon, and P.J. Skuce, 2010: Climate change and infectious disease: helminthological challenges to farmed ruminants in temperate regions. *Animal*, **4(3)**, 377-392.

Van Dingenen, R., F.J. Dentener, F. Raes, M.C. Krol, L. Emberson, and J. Cofala, 2009: The global impact of ozone on agricultural crop yields under current and future air quality legislation. *Atmospheric Environment*, **43(3)**, 604-2310.

Van Mantgem, P.J., N.L. Stephenson, J.C. Byrne, L.D. Daniels, J.F. Franklin, P.Z. Fulé, M.E. Harmon, A.J. Larson, J.M. Smith, and A.H. Taylor, 2009: Widespread increase of tree mortality rates in the western United States. *Science*, **323(5913)**, 521-524.

Van Oldenborgh, G.J., A. Van Urk, and M. Allen, 2012: The absence of a role of climate change in the 2011 Thailand floods. In: Explaining extreme events of 2011 from a climate perspective [Peterson, T.C., P.A. Stone, and S. Herring (eds.)]. *Bulletin of the American Meteorological Society*, **93(7)**, 1047-1049.

Vaquer-Sunyer, R. and C.M. Duarte, 2011: Temperature effects on oxygen thresholds for hypoxia in marine benthic organisms. *Global Change Biology*, **17(5)**, 1788-1797.

Véran, S., O. Gimenez, E. Flint, W.L. Kendall, P.F.J. Doherty, and J.D. Lebreton, 2007: Quantifying the impact of longline fisheries on adult survival in the black-footed albatross. *Journal of Applied Ecology*, **44(5)**, 942-952.

Veron, J.E., O. Hoegh-Guldberg, T.M. Lenton, J.M. Lough, D.O. Obura, P. Pearce-Kelly, C.R. Sheppard, M. Spalding, M.G. Stafford-Smith, and A.D. Rogers, 2009: The coral reef crisis: the critical importance of <350 ppm CO_2. *Marine Pollution Bulletin*, **58(10)**, 1428-1436.

Vilímek, V., M.L. Zapata, J. Klimeš, Z. Patzelt, and N. Santillán, 2005: Influence of glacial retreat on natural hazards of the Palcacocha Lake area, Peru. *Landslides*, **2(2)**, 107-115.

Villarini, G., F. Serinaldi, J.A. Smith, and W.F. Krajewski, 2009: On the stationarity of annual flood peaks in the continental United States during the 20th century. *Water Resources Research*, **45(8)**, W08417, doi:10.1029/2008WR007645.

Voigt, T., H.M. Füssel, I. Gärtner-Roer, C. Huggel, C. Marty, and M. Zemp (eds.), 2011: *Impacts of Climate Change on Snow, Ice, and Permafrost in Europe: Observed Trends, Future Projections, and Socio-Economic Relevance*. ETC/ACC Technical Paper 2010/13, Prepared by the European Topic Centre on Air and Climate Change (ETC/ACC) with the Department of Geography of the University of Zuerich, the WSL Institute for Snow and Avalanche Research (SLF) Davos and others for the European Environment Agency (EEA), ETC/ACC, Bilthoven, Netherlands, 117 pp.

Vongraven, D. and E. Richardson, 2011: Biodiversity – status and trends of polar bears. In: *Arctic Report Card: Update for 2011* [Richter-Menge, J., M.O. Jeffries, and J.E. Overland (eds.)]. National Oceanic and Atmospheric Administration (NOAA) Arctic Research Program, NOAA Office of Oceanic and Atmospheric Research, Silver Spring, MD, USA, pp. 75-78, www.arctic.noaa.gov/reportcard.

Vorogushyn, S. and B. Merz, 2012: What drives flood trends along the Rhine River: climate or river training? *Hydrology and Earth System Sciences Discussions*, **9**, 13537-13567.

Vuille, M., B. Francou, P. Wagnon, I. Juen, G. Kaser, B.G. Mark, and R.S. Bradley, 2008: Climate change and tropical Andean glaciers: past, present and future. *Earth Science Reviews*, **89(3-4)**, 79-96.

Walker, D.A., H. Epstein, M. Raynolds, P. Kuss, M. Kopecky, G.V. Frost, F. Daniëls, M. Leibman, N. Moskalenko, and G. Matyshak, 2012: Environment, vegetation and greenness (NDVI) along the North America and Eurasia Arctic transects. *Environmental Research Letters*, **7(1)**, 015504, doi:10.1088/1748-9326/7/1/015504.

Walker, M.D., C.H. Wahren, R.D. Hollister, G.H.R. Henry, L.E. Ahlquist, J.M. Alatalo, M.S. Bret-Harte, M.P. Calef, T.V. Callaghan, A.B. Carroll, H.E. Epstein, I.S. Jónsdóttir, J.A. Klein, B. Magnússon, U. Molau, S.F. Oberbauer, S.P. Rewa, C.H. Robinson, G.R. Shaver, K.N. Suding, C.C. Thompson, A. Tolvanen, Ø. Totland, P.L. Turner, C.E. Tweedie, P.J. Webber, and P.A. Wookey, 2006: Plant community responses to experimental warming across the tundra biome. *Proceedings of the National Academy of Sciences of the United States of America*, **103(5)**, 1342-1346.

Walther, G., A. Roques, P.E. Hulme, M.T. Sykes, P. Pyšek, I. Kühn, M. Zobel, S. Bacher, Z. Botta-Dukát, H. Bugmann, B. Czúcz, J. Dauber, T. Hickler, V. Jarošík, M. Kenis, S. Klotz, D. Minchin, M. Moora, W. Nentwig, J. Ott, V.E. Panov, B. Reineking, C. Robinet, V. Semenchenko, W. Solarz, W. Thuiller, M. Vilà, K. Vohland, and J. Settele, 2009: Alien species in a warmer world: risks and opportunities. *Trends in Ecology & Evolution*, **24(12)**, 686-693.

Wang, A., D.P. Lettenmaier, and J. Sheffield, 2011: Soil moisture drought in China, 1950-2006. *Journal of Climate*, **24(13)**, 3257-3271.

Wang, G., S. Sun, and R. Mei, 2011: Vegetation dynamics contributes to the multi-decadal variability of precipitation in the amazon region. *Geophysical Research Letters*, **38(19)**, L19703, doi:10.1029/2011GL049017.

Wang, M., J.E. Overland, D.B. Percival, and H.O. Mofjeld, 2006: Change in the arctic influence on Bering Sea climate during the twentieth century. *International Journal of Climatology*, **26(4)**, 531-539.

Wang, S.-Y., R.E. Davies, W.-R. Huang, and R.R. Gillies, 2011: Pakistan's two-stage monsoon and links with the recent climate change. *Journal of Geophysical Research: Atmospheres*, **116(D16)**, D16114, doi:10.1029/2011JD015760.

Wassenaar, T., P. Gerber, P.H. Verburg, M. Rosales, M. Ibrahim, and H. Steinfeld, 2007: Projecting land use changes in the Neotropics: the geography of pasture expansion into forest. *Global Environmental Change: Human and Policy Dimensions*, **17(1)**, 86-104.

Wassmann, P. and T.M. Lenton, 2012: Arctic tipping points in a Earth system perspective. *Ambio*, **41**, 1-9.

Wassmann, R., S.V.K. Jagadish, S. Heuer, A. Ismail, E. Redona, R. Serraj, R.K. Singh, G. Howell, H. Pathak, and K. Sumfleth, 2009: Chapter 2: Climate change affecting rice production: the physiological and agronomic basis for possible adaptation strategies. In: *Advances in Agronomy*, *Vol. 101* [Sparks, D.L. (ed.)]. Elsevier Science and Technology/Academic Press, Waltham, MA, USA, pp. 59-122.

Weatherhead, E., S. Gearheard, and R.G. Barry, 2010: Changes in weather persistence: insight from Inuit knowledge. *Global Environmental Change*, **20(3)**, 523-528.

Webb, A.P., 2006: *Analysis of Coastal Change and Erosion –Tebunginako Village*, *Abaiang*, *Kiribati.* EU EDF 8/9 – SOPAC Project Report 53: Reducing Vulnerability of Pacific ACP States, South Pacific Applied Geoscience Commission (SOPAC), SOPAC Secretariat, Suva, Fiji, 10 pp.

Webb, A.P., 2007: *Assessment of Salinity of Groundwater in Swamp Taro (Cyrtosperma Chamissonis) "Pulaka" Pits in Tuvalu.* EU EDF8 – SOPAC Project Report 75: Reducing Vulnerability of Pacific ACP States, South Pacific Applied Geoscience Commission (SOPAC), SOPAC Secretariat, Suva, Fiji, 37 pp.

Webb, L.B., P.H. Whetton, J. Bhend, R. Darbyshire, P.R. Briggs, and E.W.R. Barlow, 2012: Earlier wine-grape ripening driven by climatic warming and drying and management practices. *Nature Climate Change*, **2(4)**, 259-264.

Webster, P.J., V.E. Toma, and H.M. Kim, 2011: Were the 2010 Pakistan floods predictable? *Geophysical Research Letters*, **38(4)**, L04806, doi:10.1029/2010GL046346.

Wegren, S.K., 2011: Food security and Russia's 2010 drought. *Eurasian Geography and Economics*, **52**, 140-156.

Welch, J.R., J.R. Vincent, M. Auffhammer, P.F. Moya, A. Dobermann, and D. Dawe, 2010: Rice yields in tropical/subtropical Asia exhibit large but opposing sensitivities to minimum and maximum temperatures. *Proceedings of the National Academy of Sciences of the United States of America*, **107(33)**, 14562-14567.

Welker, C. and E. Faust, 2013: Tropical cyclone-related socio-economic losses in the western North Pacific region. *Natural Hazards and Earth System Sciences*, **13**, 115-124.

Welp, L., J. Randerson, and H. Liu, 2007: The sensitivity of carbon fluxes to spring warming and summer drought depends on plant functional type in boreal forest ecosystems. *Agricultural and Forest Meteorology*, **147(3)**, 172-185.

Wernberg, T., B.D. Russell, P.J. Moore, S.D. Ling, D.A. Smale, A. Campbell, M.A. Coleman, P.D. Steinberg, G.A. Kendrick, and S.D. Connell, 2011a: Impacts of climate change in a global hotspot for temperate marine biodiversity and ocean warming. *Journal of Experimental Marine Biology and Ecology*, **400(1)**, 7-16.

Wernberg, T., B.D. Russell, M.S. Thomsen, C.F.D. Gurgel, C.J.A. Bradshaw, E.S. Poloczanska, and S.D. Connell, 2011b: Seaweed communities in retreat from ocean warming. *Current Biology*, **21(21)**, 1828-1832.

Wernberg, T., D.A. Smale, F. Tuya, M.S. Thomsen, T.J. Langlois, T. de Bettignies, S. Bennett, and C.S. Rousseaux, 2012: An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. *Nature Climate Change*, **3(1)**, 78-82.

Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam, 2006: Warming and earlier spring increases Western U.S. forest fire activity. *Science*, **313(5789)**, 940-943.

Westra, S., L.V. Alexander, and F.W. Zwiers, 2013: Global increasing trends in annual maximum daily precipitation. *Journal of Climate*, **26(11)**, 3904-3918.

Wethey, D.S. and S.A. Woodin, 2008: Ecological hindcasting of biogeographic responses to climate change in the European intertidal zone. *Hydrobiologia*, **606(1)**, 139-151.

Weyhenmeyer, G.A., D.M. Livingstone, M. Meili, O. Jensen, B. Benson, and J.J. Magnuson, 2011: Large geographical differences in the sensitivity of ice-covered lakes and rivers in the Northern Hemisphere to temperature changes. *Global Change Biology*, **17(1)**, 268-275.

Wezel, A. and A.M. Lykke, 2006: Woody vegetation change in Sahelian West Africa: evidence from local knowledge. *Environment, Development, and Sustainability*, **8**, 553-567.

WGMS, 2008: *Global Glacier Changes. Facts and Figures* [Zemp, M., I. Roer, A. Kääb, M. Hoelzle, F. Paul, and W. Haeberli (eds.)]. World Glacier Monitoring Service (WGMS), Published by the United Nations Environment Programme (UNEP), Nairobi, Kenya and the World Glacier Monitoring Service (WGMS), University of Zurich, Zurich, Switzerland, 88 pp.

White, I. and T. Falkland, 2010: Management of freshwater lenses on small Pacific islands. *Hydrogeology Journal*, **18(1)**, 227-246.

White, I., T. Falkland, T. Metutera, E. Metai, M. Overmars, P. Perez, and A. Dray, 2007a: Climatic and human influences on groundwater in low atolls. *Vadose Zone Journal*, **6(3)**, 581-590.

White, I., T. Falkland, P. Perez, A. Dray, T. Metutera, E. Metai, and M. Overmars, 2007b: Challenges in freshwater management in low coral atolls. *Journal of Cleaner Production*, **15(16)**, 1522-1528.

White, S., 2011: *The Climate of Rebellion in the Early Modern Ottoman Empire.* Cambridge University Press, New York, NY, USA, 354 pp.

Wilbanks, T.J., P. Romero Lankao, M. Bao, F. Berkhout, S. Cairncross, J.-P. Ceron, M. Kapshe, R. Muir-Wood, and R. Zapata-Marti, 2007: Industry, settlement and society. In: *Climate Change 2007: Impacts*, *Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P. Van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 357-390.

Wilkinson, C., O. Linden, H. Cesar, G. Hodgson, J. Rubens, and A.E. Strong, 1999: Ecological and socioeconomic impacts of 1998 coral mortality in the Indian Ocean: an ENSO impact and a warning of future change? *Ambio*, **28(2)**, 188-196.

Williams, A.P., C.D. Allen, A.K. Macalady, D. Griffin, C.A. Woodhouse, D.M. Meko, T.W. Swetnam, S.A. Rauscher, R. Seager, and H.D. Grissino-Mayer, 2012: Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change*, **3**, 292-297.

Wohling, M., 2009: The problem of scale in indigenous knowledge: a perspective from Northern Australia. *Ecology and Society*, **14(1)**, 1-14.

Wolken, J.M., T.N. Hollingsworth, T.S. Rupp, F.S. Chapin, S.F. Trainor, T.M. Barrett, P.F. Sullivan, A.D. McGuire, E.S. Euskirchen, P.E. Hennon, E.A. Beever, J.S. Conn, L.K. Crone, D.V. D'Amore, N. Fresco, T.A. Hanley, K. Kielland, J.J. Kruse, T. Patterson, E.A.G. Schuur, D.L. Verbyla, and J. Yarie, 2011: Evidence and implications of recent and projected climate change in Alaska's forest ecosystems. *Ecosphere*, **2(11)**, 124, doi:10.1890/ES11-00288.1.

Woodworth, P.L., M. Menéndez, and W. Roland Gehrels, 2011: Evidence for century-timescale acceleration in mean sea levels and for recent changes in extreme sea levels. *Surveys in Geophysics*, **32(4)**, 603-618.

Wootton, J.T., C.A. Pfister, and J.D. Forester, 2008: Dynamic patterns and ecological impacts of declining ocean pH in a high-resolution multi-year dataset. *Proceedings of the National Academy of Sciences of the United States of America*, **105(48)**, 18848-18853.

World Bank, 2012: *Thai Flood 2011: Rapid Assessment for Resilient Recovery and Reconstruction Planning.* Working Paper No. 69822, Vol. 2, The International Bank for Reconstruction and Development / The World Bank, World Bank Publishing, Washington, DC, USA, 377 pp., documents.worldbank.org/curated/en/docsearch/report/69822.

World Bank and ADB, 2010: *Pakistan Floods 2010: Preliminary Floods Damage and Needs Assessment.* Asian Development Bank (ADB) and the World Bank, Islamabad, Pakistan, 184 pp.

Wulf, H., B. Bookhagen, and D. Scherler, 2012: Climatic and geologic controls on suspended sediment flux in the Sutlej River Valley, western Himalaya. *Hydrology and Earth System Sciences*, **16(7)**, 2193-2217.

Xu, J., R.E. Grumbine, A. Shrestha, M. Eriksson, X. Yang, Y. Wang, and A. Wilkes, 2009: The melting Himalayas: cascading effects of climate change on water, biodiversity, and livelihoods. *Conservation Biology*, **23(3)**, 520-530.

Xu, K., J.D. Milliman, Z. Yang, and H. Xu, 2008: Climatic and anthropogenic impacts on water and sediment discharges from the Yangtze River (Changjiang), 1950-2005. In: *Large Rivers: Geomorphology and Management* [Gupta, A. (ed.)]. John Wiley & Sons, Chichester, UK, pp. 609-626.

Xu, L., R.B. Myneni, F.S. Chapin III, T.V. Callaghan, J.E. Pinzon, C.J. Tucker, Z. Zhu, J. Bi, P. Ciais, H. Tommervik, E.S. Euskirchen, B.C. Forbes, S.L. Piao, B.T. Anderson, S. Ganguly, R.R. Nemani, S.J. Goetz, P.S.A. Beck, A.G. Bunn, C. Cao, and J.C. Stroeve, 2013: Temperature and vegetation seasonality diminishment over northern lands. *Nature Climate Change*, **3**, 581-586.

Yamano, H., H. Kayanne, T. Yamaguchi, Y. Kuwhara, H. Yokoki, H. Shimazaki, and M. Chicamori, 2007: Atoll island vulnerability to flooding and inundation revealed by historical reconstruction. Fongafale Island, Funafuti Atoll, Tuvalu. *Global and Planetary Change*, **57(3-4)**, 407-416.

Yamano, H., K. Sugihara, and K. Nomura, 2011: Rapid poleward range expansion of tropical reef corals in response to rising sea surface temperatures. *Geophysical Research Letters*, **38(4)**, L04601, doi:10.1029/2010GL046474.

Yang, Z., J. Gao, L. Zhao, X. Xu, and H. Ouyang, 2013: Linking thaw depth with soil moisture and plant community composition: effects of permafrost degradation on alpine ecosystems on the Qinghai-Tibet Plateau. *Plant and Soil*, **367(1-2)**, 687-700.

Yao, T., L. Thompson, W. Yang, W. Yu, Y. Gao, X. Guo, X. Yang, K. Duan, H. Zhao, B. Xu, J. Pu, A. Lu, Y. Xiang, D.B. Kattel, and D. Joswiak, 2012: Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nature Climate Change*, **2(9)**, 663-667.

Yli-Panula, E., D.B. Fekedulegn, B.J. Green, and H. Ranta, 2009: Analysis of airborne betula pollen in Finland; a 31-year perspective. *International Journal of Environmental Research and Public Health*, **6(6)**, 1706-1723.

You, L., M.W. Rosegrant, S. Wood, and D. Sun, 2009: Impact of growing season temperature on wheat productivity in China. *Agricultural and Forest Meteorology*, **149(6)**, 1009-1014.

Zemp, M., M. Hoelzle, and W. Haeberli, 2009: Six decades of glacier mass-balance observations: a review of the worldwide monitoring network. *Annals of Glaciology*, **50(50)**, 101-111.

Zhang, D.D., H.F. Lee, C. Wang, B. Li, Q. Pei, J. Zhang, and Y. An, 2011: The causality analysis of climate change and large-scale human crisis. *Proceedings of the National Academy of Sciences of the United States of America*, **108(42)**, 17296-17301.

Zhang, G.H., S.H. Fu, W.H. Fang, H. Imura, and X.C. Zhang, 2007: Potential effects of climate change on runoff in the yellow river basin of China. *Transactions of the American Society of Agricultural and Biological Engineers (ABASE)*, **50(3)**, 911-918.

Zhang, S., X.X. Lu, D.L. Higgitt, C.T.A. Chen, J. Han, and H. Sun, 2008: Recent changes of water discharge and sediment load in the Zhujiang (Pearl River) Basin, China. *Global and Planetary Change*, **60(3)**, 365-380.

Zhang, Y., S. Liu, J. Xu, and D. Shangguan, 2008: Glacier change and glacier runoff variation in the Tuotuo River basin, the source region of Yangtze River in western China. *Environmental Geology*, **56(1)**, 59-68.

Ziervogel, G. and A. Opere (eds.), 2010: *Integrating Meteorological and Indigenous Knowledge-Based Seasonal Climate Forecasts for the Agricultural Sector: Lessons from Participatory Action Research in sub-Saharan Africa*. CCAA Learning Paper Series, Climate Change Adaptation in Africa (CCAA) Program, UK Department for International Development (DIFD) and the International Development Research Centre (IDRC), IDRC, Ottawa, ON, Canada, 19 pp.

Ziska, L., K. Knowlton, C. Rogers, D. Dalan, N. Tierney, M.A. Elder, W. Filley, J. Shropshire, L.B. Ford, C. Hedberg, P. Fleetwood, K.T. Hovanky, T. Kavanaugh, G. Fulford, R.F. Vrtis, J.A. Patz, J. Portnoy, F. Coates, L. Bielory, and D. Frenz, 2011: Recent warming by latitude associated with increased length of ragweed pollen season in central North America. *Proceedings of the National Academy of Sciences of the United States of America*, **108(10)**, 4248-4251.

Zwiers, F.W., X. Zhang, and Y. Feng, 2011: Anthropogenic influence on long return period daily temperature extremes at regional scales. *Journal of Climate*, **24(3)**, 881-892.

19

Emergent Risks and Key Vulnerabilities

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This chapter should be cited as:

Oppenheimer, M., M. Campos, R. Warren, J. Birkmann, G. Luber, B. O'Neill, and K. Takahashi, 2014: Emergent risks and key vulnerabilities. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1039-1099.

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Executive Summary

This chapter assesses climate-related risks in the context of Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC). {Box 19.1} Such risks arise from the interaction of the evolving exposure and vulnerability of human, socioeconomic, and biological systems with changing physical characteristics of the climate system. {19.2} Alternative development paths influence risk by changing the likelihood of climatic events and trends (through their effects on greenhouse gases (GHGs) and other emissions) and by altering vulnerability and exposure. {19.2.4, Figure 19-1, Box 19-2}

Interactions of climate change impacts on one sector with changes in exposure and vulnerability, as well as adaptation and mitigation actions affecting the same or a different sector are generally not included or well integrated into projections of risk. However, their consideration leads to the identification of a variety of emergent risks {Box 19-2} that were not previously assessed or recognized (*high confidence*). {19.3} This chapter identifies several such complex system interactions that increase vulnerability and risk synergistically. For example:

- **The risk of climate change to human systems (e.g., agriculture and water supply) is increased by the loss of ecosystem services that are supported by biodiversity** (e.g., water purification, protection from extreme weather events, preservation of soils, recycling of nutrients, and pollination of crops) (*high confidence*). Studies since the Fourth Assessment Report (AR4) broadly confirm that a large proportion of species are at increased risk of extinction at all but the lowest levels of warming. {19.3.2.1, 19.5.1, 19.6.3.5}
- **Risks result from the management of water, land, and energy in the context of climate change.** For example, in some water stressed regions, as groundwater stores that have historically acted as buffers against impacts of climate variations and change are depleted, adverse consequences arise for human systems and ecosystems simultaneously undergoing alteration of regional groundwater resources due to climate change. The production of bioenergy crops to mitigate climate change leads to land conversion (e.g., from food crops and unmanaged ecosystems to energy crops; *high confidence*) and in some scenarios, reduced food security as well as additional GHG emissions over the course of decades or centuries. {19.3.2.2}
- **Climate change has the potential to adversely affect human health by increasing exposure and vulnerability to a variety of stresses.** For example, the interaction of climate change with food security can exacerbate malnutrition, increasing vulnerability of individuals to a range of diseases (*high confidence*). {19.3.2.3}
- **The risk of severe harm and loss due to climate change-related hazards and various vulnerabilities is particularly high in large urban and rural areas in low-lying coastal zones (*high confidence*).** These areas, many characterized by increasing populations, are exposed to multiple hazards and potential failures of critical infrastructure, generating new systemic risks. Cities in Asian megadeltas, where populations are subject to sea level rise, storm surge, coastal erosion, saline intrusion, and flooding, provide an example. {19.2.3, 19.3.2.4, 19.4.2.1, 19.6.1.3.1, 19.6.2.1, 19.7.5, Table 19-4}
- **Spatial convergence of impacts in different sectors creates compound risk in many areas (*medium confidence*).** Examples include the Arctic (where thawing and sea ice loss disrupt land transportation, buildings, other infrastructure, and are projected to disrupt indigenous culture); and the environs of Micronesia, Mariana Island, and Papua New Guinea (where coral reefs are highly threatened due to exposure to concomitant sea surface temperature rise and ocean acidification). {19.3.2.4}

Emergent risks also arise from indirect, trans-boundary, and long-distance impacts of climate change. Adaptive responses and mitigation measures sometimes increase such risks (*high confidence*). {19.4} Human or ecological responses to local impacts of climate change can generate harm at distant places.

- Increasing prices of food commodities on the global market due to local climate impacts, in conjunction with other stressors, decrease food security and exacerbate food insecurity at distant locations. {19.4.1}
- Climate change will bear significant consequences for human migration flows at particular times and places, creating risks as well as benefits for migrants and for sending and receiving regions and states (*high confidence*). {19.4.2.1}
- The effect of climate change on conflict and insecurity is an emergent risk because factors such as poverty and economic shocks that are associated with a higher risk of violent conflict are themselves sensitive to climate change. In numerous statistical studies, the influence of climate variability on violent conflict is large in magnitude (*medium confidence*). {19.4.2.2}
- Many species shift their ranges in response to climate change, adversely affecting ecosystem function and services while presenting new challenges to conservation efforts (*medium confidence*). {19.4.2.3}

- Mitigation measures taken in one location can have long-distance or indirect impacts on biodiversity and/or human systems. For example, the development of biofuels as energy sources can increase food prices (*high confidence*) and affect distant land use practices. {19.4.1, 19.4.3}

Additional risks related to particular biophysical impacts of climate change have arisen recently in the literature in sufficient detail to permit assessment (*high confidence*). {19.5}

- **Risks associated with global temperature rise in excess of 4°C relative to preindustrial levels[1] arise** from severe and widespread impacts on unique and threatened systems, substantial species extinction, extensive loss of ecosystem functioning, large risks to global and regional food security, and the combination of high temperature and humidity compromising normal human activities, including growing food or working outdoors in some areas for parts of the year (*high confidence*) and the potential for traversing thresholds that lead to disproportionately large Earth systems responses (*medium confidence*). {19.5.1}
- **Ocean acidification poses risks to marine ecosystems and the societies that depend on them.** For example, ocean acidification is *very likely* to lead to changes in coral calcification rates. Reduced coral calcification is projected to have impacts of medium to high magnitude on some ecosystem services, including tourism and the provisioning of fishing. {19.5.2}
- **There is increasing evidence in the literature that high ambient carbon dioxide (CO_2) concentrations in the atmosphere will affect human health by increasing the production and allergenicity of pollen and allergenic compounds and by decreasing nutritional quality of important food crops. {19.5.3}**
- **In addition to providing potential climate change abatement benefits, geoengineering poses widespread risks to society and ecosystems.** For example, in some model experiments the implementation of Solar Radiation Management (SRM) for the purpose of limiting global warming leads to ozone depletion and reduces precipitation. In addition, the failure or abrupt halting of SRM risks rapid climate change. {19.5.4}

Global, regional, and local socioeconomic, environmental, and governance trends indicate that vulnerability and exposure of communities or social-ecological systems to climatic hazards related to extreme events are dynamic and thus vary across temporal and spatial scales (*high confidence*). Effective risk reduction and adaptation strategies consider these dynamics and the inter-linkages between socioeconomic development pathways and the vulnerability and exposure of people. Changes in poverty or socioeconomic status, ethnic composition, age structure, and governance had a significant influence on the outcome of past crises associated with climatic hazards. {19.6.1}

Challenges for vulnerability reduction and adaptation actions are particularly high in regions that have shown severe difficulties in governance. Studies confirm that countries that are classified as failed states and afflicted by violence are often not able to reduce vulnerability effectively. Unless governance improves in countries with severe governance failure, risk will increase as a result of climate changes interacting with increased human vulnerability (*high confidence*). {19.6.1.3.3}

***Key risks* inform evaluation of "dangerous anthropogenic interference with the climate system," in the terminology of UNFCCC Article 2. These are potentially severe adverse consequences for humans and social-ecological systems resulting from the interaction of hazards linked to climate change and the vulnerability of exposed societies and systems. Key risks were identified in this assessment based on expert judgments made by authors of the various chapters of this report in light of criteria described here {19.2.2.2} and consolidated into the following representative list (*high confidence*).** {19.2.2.2, 19.6.2.1, Table 19-4, Boxes 19-2 and CC-KR} (Roman numerals indicate corresponding entries in Table 19-4; notation at end of each entry indicates corresponding Reasons for Concern (RFCs), discussed below.)

[1] Levels of global mean temperature change are variously presented in the literature with respect to "preindustrial" temperatures in a specified year or period, e.g., 1850–1900. Alternatively, the average temperature within a recent period, e.g., 1986–2005, is used as a baseline. In this chapter, we use both, depending on the literature being assessed. The increase above preindustrial (1850–1900) levels for the period 1986–2005 is estimated at 0.61°C (WGI AR5 Section 11.3.6.3). For example, using these baselines, a 2°C increase above preindustrial levels corresponds to a 1.39°C increase above 1986–2005 levels. We use other baselines on occasion depending on the literature cited and explicitly indicate where this is the case. Climate impact studies often report outcomes as a function of regional temperature change, which can differ significantly from changes in global mean temperature. In most land areas, regional warming is larger than global warming (WGI AR5 Section 10.3.1.1.2). However, given the many conventions in the literature for baseline periods, readers are advised to check carefully and to adjust baseline levels for consistency when comparing outcomes.

i) Risk of death, injury, ill-health, or disrupted livelihoods in low-lying coastal zones and small island developing states and other small islands, due to storm surges, coastal flooding, and sea level rise. [RFC 1-5]
ii) Risk of severe ill-health and disrupted livelihoods for large urban populations due to inland flooding in some regions. [RFC 2 and 3]
iii) Systemic risks due to extreme weather events leading to breakdown of infrastructure networks and critical services such as electricity, water supply, and health and emergency services. [RFC 2-4]
iv) Risk of mortality and morbidity during periods of extreme heat, particularly for vulnerable urban populations and those working outdoors in urban or rural areas. [RFC 2 and 3]
v) Risk of food insecurity and the breakdown of food systems linked to warming, drought, flooding, and precipitation variability and extremes, particularly for poorer populations in urban and rural settings. [RFC 2-4]
vi) Risk of loss of rural livelihoods and income due to insufficient access to drinking and irrigation water and reduced agricultural productivity, particularly for farmers and pastoralists with minimal capital in semi-arid regions. [RFC 2 and 3]
vii) Risk of loss of marine and coastal ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for coastal livelihoods, especially for fishing communities in the tropics and the Arctic. [RFC 1, 2, and 4]
viii) Risk of loss of terrestrial and inland water ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for livelihoods. [RFC 1, 3, and 4]

Climate change risks vary substantially across plausible alternative development pathways and the relative importance of development and climate change varies by sector, region, and time period; both are important to understanding possible outcomes (*high confidence*). In some cases, there is substantial potential for adaptation to reduce risks, with development pathways playing a key role in determining challenges to adaptation, including through their effects on ecosystems and ecosystem services. {19.6.2.2}

Assessment of the RFC framework pertinent to Article 2 of the UNFCCC has led to evaluations of risk being updated in light of the advances since the AR4. {19.6.3} (All temperature changes are relative to 1986–2005, i.e., "recent." Numbers are indicative of RFC designation in key risk enumeration, above.)

1. **Unique and threatened systems**: Some unique and threatened systems, including ecosystems and cultures, are already at risk from climate change (*high confidence*). The number of such systems at risk of severe consequences is higher with additional warming of around 1°C. Many species and systems with limited adaptive capacity are subject to very high risks with additional warming of 2°C, particularly Arctic-sea-ice and coral-reef systems. {19.6.3.2}
2. **Extreme weather events**: Climate-change-related risks from extreme events, such as heat waves, extreme precipitation, and coastal flooding, are already moderate (*high confidence*) and high with 1°C additional warming (*medium confidence*). Risks associated with some types of extreme events (e.g., extreme heat) increase further at higher temperatures (*high confidence*). {19.6.3.3}
3. **Distribution of impacts**: Risks are unevenly distributed and are generally greater for disadvantaged people and communities in countries at all levels of development. Risks are already moderate because of regionally differentiated climate-change impacts on crop production in particular (*medium* to *high confidence*). Based on projected decreases in regional crop yields and water availability, risks of unevenly distributed impacts are high for additional warming above 2°C (*medium confidence*). {19.6.3.4}
4. **Global aggregate impacts**: Risks of global aggregate impacts are moderate for additional warming between 1-2°C, reflecting impacts to both Earth's biodiversity and the overall global economy (*medium confidence*). Extensive biodiversity loss with associated loss of ecosystem goods and services results in high risks around 3°C additional warming (*high confidence*). Aggregate economic damages accelerate with increasing temperature (*limited evidence*, *high agreement*), but few quantitative estimates have been completed for additional warming around 3°C or above. {19.3.2.1, 19.5.1, 19.6.3.5}
5. **Large-scale singular events**: With increasing warming, some physical systems or ecosystems may be at risk of abrupt and irreversible changes. Risks associated with such tipping points become moderate between 0-1°C additional warming, due to early warning signs that both warm-water coral reef and Arctic ecosystems are already experiencing irreversible regime shifts (*medium confidence*). Risks increase disproportionately as temperature increases between 1-2°C additional warming and become high above 3°C, due to the potential for a large and irreversible sea level rise from ice sheet loss. For sustained warming greater than some threshold, near-complete loss of the Greenland ice sheet would occur over a millennium or more, contributing up to 7 m of global mean sea level rise. {19.6.3.6}

Impacts of climate change avoided under a range of scenarios for mitigation of GHG emissions are potentially large and increasing over the 21st century (*high confidence*). {19.7.1} Among the impacts assessed here, benefits from mitigation are most immediate for surface ocean acidification and least immediate for impacts related to sea level rise. Because mitigation reduces the rate as well as the magnitude of warming, it also increases the time available for adaptation to a particular level of climate change, potentially by several decades.

Only mitigation scenarios in the most stringent category (i.e., with 2100 CO_2-eq concentrations of 430 to 480 ppm) maintain moderately healthy coral reefs (*medium confidence*). With respect to the RFCs, only the most stringent of scenarios in this category constrain overall risks to unique and threatened systems, and those associated with extreme weather events to a moderate level, while the other scenarios in this category create risk in the high range for these two RFCs. The most stringent among these scenarios constrain the level of risk associated with all other RFCs to the moderate level (*high confidence*). {19.6.3.2-3, 19.7.1}

The higher part of the range of GHG emission scenarios in the literature, that is, those with 2100 CO_2-eq concentrations above 720 ppm create risks associated with extreme weather events and large-scale singular events that are in the high range, and very high range (reflecting inability to adapt) for unique and threatened systems. Risks associated with the distribution of impacts increase toward the very high range (*high confidence*). Risks of global aggregate impacts transition from moderate to high as CO_2-eq concentrations increase from 720 ppm. {19.6.3.2, 19.6.3.4, 19.7.1}

Under any plausible scenario for mitigation and adaptation, some degree of risk from residual damages is unavoidable (*very high confidence*). For example, very few integrated assessment model-based scenarios in the literature demonstrate the feasibility of limiting warming to a maximum of 1.5°C with at least 50% likelihood. {19.7.1-2}

The risk of crossing tipping points (critical thresholds) in the Earth system or socio-ecological systems is projected to decrease with reduced GHG emissions {19.7.3}, and the risk of crossing tipping points in socio-ecological systems can also be reduced by reducing human vulnerability or by preserving ecosystem services, or both (*medium confidence*). {19.7.4} The risk of crossing tipping points is reduced by limiting the level of climate change and/or removing concomitant stresses such as overgrazing, overfishing, and pollution, but there is *low confidence* in the level of climate change associated with such tipping points and measures to avoid them.

19.1. Purpose, Scope, and Structure of this Chapter

The objective of this chapter is to assess new literature published since the Fourth Assessment Report (AR4) on emergent risks and key vulnerabilities to climate change from the perspective of the distribution of risk over geographic location, economic sector, time period, and socioeconomic characteristics of individuals and societies. Frameworks used in previous IPCC reports to assess risk in the context of Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) are updated and extended in light of new literature, and additional frameworks arising in recent literature are examined. A focal point of this chapter is the interaction of the changing physical characteristics of the climate system with evolving characteristics of socioeconomic and biological systems (exposure and vulnerability) to produce risk (see Figure 19-1). Given the centrality of Article 2 to this chapter, the greater emphasis is on harmful outcomes of climate change rather than potential benefits.

19.1.1. Historical Development of this Chapter

The Third and Fourth Assessment Reports (TAR and AR4, respectively) each devoted chapters to evaluating the state of knowledge relevant to Article 2 of the UNFCCC (Smith et al., 2001; Schneider et al., 2007; see Box 19-1). The TAR sorted and aggregated impacts discussed in the literature according to a framework called Reasons for Concern (RFCs), and assessed the level of risk associated with individual impacts of climate change as well as each category or "reason" as a whole, generally as a function of global mean warming. This assessment took account of the distribution of vulnerability across particular regions, countries, and sectors.

AR4 furthered the discussion relevant to Article 2 by assessing new literature and developing criteria potentially useful for policy makers in the determination of key impacts and vulnerabilities, that is, those meriting particular attention in respect to Article 2. See Box 19-2 for definitions of Reasons for Concern, Key Vulnerabilities (KVs), and related terms. Some definitions go beyond those in the Glossary to provide details especially pertinent to this chapter.

AR4 emphasized the differences in vulnerability between developed and developing countries but also assessed new literature describing vulnerability pertaining to various aggregations of people (such as by ethnic, cultural, age, gender, or income status) and response strategies for avoiding key impacts. The RFCs were updated and the Synthesis Report (IPCC, 2007a) noted that they "remain a viable framework to consider key vulnerabilities" (IPCC, 2007a, Section 5.2). However, their

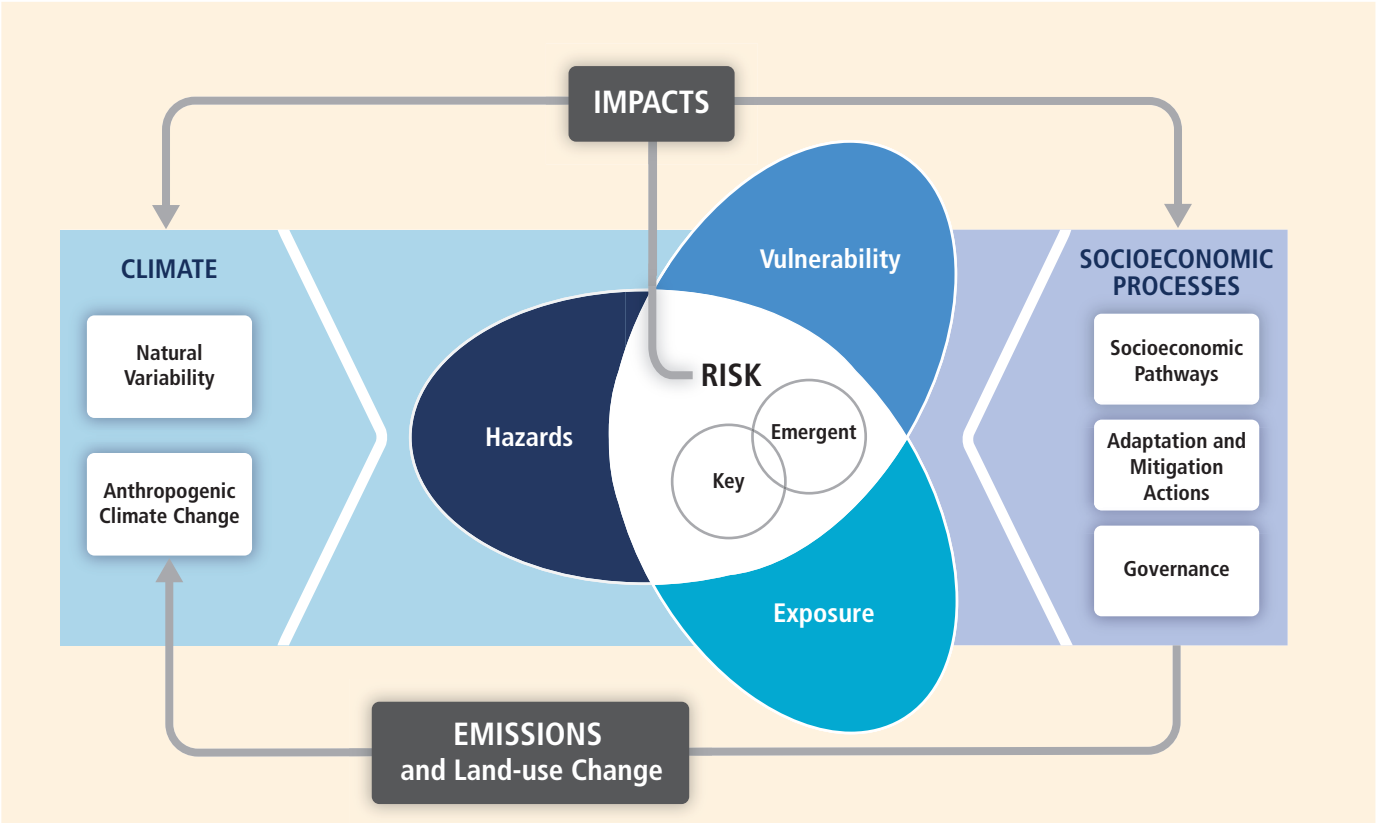


Figure 19-1 | Schematic of the interaction among the physical climate system, exposure, and vulnerability producing risk. The figure visualizes the different terms and concepts discussed in this chapter. Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems. The definition and use of "key" and "emergent" are indicated in Box 19-2 and the Glossary. Vulnerability and exposure are, as the figure shows, largely the result of socioeconomic pathways and societal conditions (although changing hazard patterns also play a role; see Section 19.6.1.1). Changes in both the climate system (left side) and socioeconomic processes (right side) are central drivers of the different core components (vulnerability, exposure, and hazards) that constitute risk (modified version of SREX Figure SPM.1 (IPCC, 2012a)).

utility was limited by several factors: the lack of a time dimension (i.e., representation of impacts arising from timing and rates of climate change and climate forcing); the focus on risk only as a function of global mean temperature; lack of a clear distinction between impacts and vulnerability; and, importantly, incomplete incorporation of the evolving socioeconomic context, particularly adaptation capacity, in representing impacts and vulnerability.

19.1.2. The Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation

The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX; IPCC, 2012a) provides additional insights with respect to two RFCs (risks associated with extreme weather events and the distribution of impacts) and particularly the distribution of capacities to adapt to extreme events across countries, communities, and other groups, and the limitations on implementation of these capacities. SREX emphasized the role of the socioeconomic setting and development pathway (expressed through exposure and vulnerability) in determining, on the one hand, the circumstances where extreme events do or do not result in extreme

Box 19-1 | Article 2 of the United Nations Framework Convention on Climate Change

Article 2

OBJECTIVE: The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

Frequently Asked Questions

FAQ 19.1 | Does science provide an answer to the question of how much warming is unacceptable?

No. Careful, critical scientific research and assessment can provide information to help society consider what levels of warming or climate change impacts are unacceptable. However, the answer is ultimately a subjective judgment that depends on values and culture, as well as socioeconomic and psychological factors, all of which influence how people perceive risk in general and the risk of climate change in particular. The question of what level of climate change impacts is unacceptable is ultimately not just a matter of the facts, but of how we feel about those facts.

This question is raised in Article 2 of the UNFCCC. The criterion, in the words of Article 2, is "dangerous anthropogenic interference with the climate system"—a framing that invokes both scientific analysis and human values.

Agreements reached by governments since 2009, meeting under the auspices of the UNFCCC, have recognized "the scientific view that the increase in global temperature should be below 2 degrees Celsius" (Section 19.1, UNFCCC, Copenhagen Accord). Still, as informed on the subject as the scientists referred to in this statement may be, theirs is just one valuable perspective. How each country or community will define acceptable or unacceptable levels, essentially deciding what is "dangerous," is a societal judgment.

Science can certainly help society think about what is unacceptable. For example, science can identify how much monetary loss might occur if tropical cyclones grow more intense or heat waves more frequent, or identify the land that might be lost in coastal communities for various levels of higher seas. But "acceptability" depends on how each community values those losses. This question is more complex when loss of life is involved and yet more so when damage to future generations is involved. These are highly emotional and controversial value propositions that science can only inform, not decide.

The purpose of this chapter is to highlight key vulnerabilities and key risks that science has identified; however, it is up to people and governments to determine how the associated impacts should be valued, and whether and how the risks should be acted upon.

Box 19-2 | Definitions

Exposure: The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.

Vulnerability: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

A broad set of factors such as wealth, social status, and gender determine vulnerability and exposure to climate-related risk.

Impacts: (Consequences, Outcomes) Effects on natural and human systems. In this report, the term *impacts* is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as *consequences* and *outcomes*. The impacts of climate change on geophysical systems, including floods, droughts, and sea level rise, are a subset of impacts called physical impacts.

Hazard: The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In this report, the term *hazard* usually refers to climate-related physical events or trends or their physical impacts.

Stressors: Events and trends, often not climate-related, that have an important effect on the system exposed and can increase vulnerability to climate-related risk.

Risk: The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur.

$$\text{Risk} = (\text{Probability of Events or Trends}) \times \text{Consequences}$$

Risk results from the interaction of vulnerability, exposure, and hazard (see Figure 19-1). In this report, the term *risk* is used primarily to refer to the risks of climate-change impacts.

Key vulnerability, key risk, key impact: A vulnerability, risk, or impact relevant to the definition and elaboration of "dangerous anthropogenic interference (DAI) with the climate system," in the terminology of United Nations Framework Convention on Climate Change (UNFCCC) Article 2, meriting particular attention by policymakers in that context.

Key risks are potentially severe adverse consequences for humans and social-ecological systems resulting from the interaction of climate-related hazards with vulnerabilities of societies and systems exposed. Risks are considered "key" due to high hazard or high vulnerability of societies and systems exposed, or both.

Vulnerabilities are considered "key" if they have the potential to combine with hazardous events or trends to result in key risks. Vulnerabilities that have little influence on climate-related risk, for instance, due to lack of exposure to hazards, would not be considered key.

Key impacts are severe consequences for humans and social-ecological systems.

Continued next page →

Box 19-2 (continued)

Extract from WGII AR4 Chapter 19:

Many impacts, vulnerabilities and risks merit particular attention by policy-makers due to characteristics that might make them 'key'. The identification of potential key vulnerabilities is intended to provide guidance to decision-makers for identifying levels and rates of climate change that may be associated with 'dangerous anthropogenic interference' (DAI) with the climate system, in the terminology of United Nations Framework Convention on Climate Change (UNFCCC) Article 2 (see Box 19-1). Ultimately, the definition of DAI cannot be based on scientific arguments alone, but involves other judgments informed by the state of scientific knowledge.

Emergent Risk: A risk that arises from the interaction of phenomena in a complex system, for example, the risk caused when geographic shifts in human population in response to climate change lead to increased vulnerability and exposure of populations in the receiving region. Many of the emergent risks discussed in this report have only recently been analyzed in the scientific literature in sufficient detail to permit assessment. In this chapter, the only emergent risks discussed are those that have the potential to become key risks once sufficient understanding accumulates.

Reasons for Concern: Elements of a classification framework, first developed in the IPCC Third Assessment Report, which aims to facilitate judgments about what level of climate change may be "dangerous" (in the language of Article 2 of the UNFCCC) by aggregating impacts, risks, and vulnerabilities.

Summary of Reasons for Concern (revised from WGII TAR Chapter 19; see also Sections 1.2.3, 18.6.4):

"Reasons for Concern" may aid readers in making their own determination about what is a "dangerous" climate change. Each Reason for Concern is consistent with a paradigm that can be used by itself or in combination with other paradigms to help determine what level of climate change is dangerous. The reasons for concern are the relations between global mean temperature increase and:

1. *Risks to unique and threatened systems*
2. *Risks associated with extreme weather events*
3. *Risks associated with the distribution of impacts*
4. *Risks associated with global aggregate impacts*
5. *Risks associated with large-scale singular events*

impacts and disasters, and on the other hand, when non-extreme events may also result in extreme impacts and disasters.

19.1.3. New Developments in this Chapter

With these frameworks already established, and a long list of impacts and key vulnerabilities enumerated and categorized in previous assessments, the current chapter has three goals: first, to recognize and assess risks that arise out of complex interactions involving climate and socio-ecological systems, called *emergent risks* (see Boxes 19-2, CC-KR; Table 19-4). In many cases, scientific literature sufficient to permit assessment of such risks has become available largely since AR4. In this chapter, we consider only those emergent risks that are relevant to interpreting Article 2 or have the potential to become relevant (see criteria in Section 19.2.2) as additional understanding accumulates. For example, since AR4, sufficient literature has emerged to allow initial assessment of the potential relationship between climate change and conflict. The second goal is to reassess and reorganize the existing frameworks (based on RFCs and KVs) for evaluating the literature pertinent to Article 2 of the UNFCCC to address the deficiencies cited in Section 19.1.1, particularly in light of the advances in SREX and the current report's discussions of vulnerability and human security (Chapters 12 and 13) and adaptation (Chapters 14 to 17 and 20). From this perspective, the objective stated in Article 2 may be viewed as aiming in part to ensure human security in the face of climate change. Third, this chapter assesses recent literature pertinent to additional frameworks for categorizing risk and vulnerability, focusing on indirect impacts and interaction and concatenation of risk, including geographic areas of compound risk (Section 19.3).

To clarify the relative roles of characteristics of the physical climate system, such as increases in temperature, precipitation, or storm frequency, and

characteristics of the socioeconomic and biological systems with which these interact (vulnerability and exposure) to produce risks of particular consequences (the latter term used interchangeably here with "impacts" and "outcomes"), we rely heavily on a concept used sparingly in the TAR and AR4, *key risks* (see Box 19-2). Furthermore, we emphasize recent literature pointing to the *dynamic* character of vulnerability and exposure based on their intimate relationship to development.

Section 19.2 describes the framework used here for identifying key vulnerabilities, key risks, and emergent risks. We consider a variety of types of emergent risks, including in Section 19.3 those arising from multiple interacting systems and stresses, and in Section 19.4, those arising from indirect impacts, trans-boundary impacts, and impacts occurring at a long distance from the location of the climate change that causes them. One example that illustrates all of these properties is the extent to which climate change impacts on agriculture, water resources, and sea level affect human migration flows. These shifts entail both risks of harm and potential benefits for the migrants, for the regions where they originate, and for the destination regions (see Sections 12.4, 19.4.2.1). Associated risks include indirect impacts, like the effect of land use changes on ecosystems occurring at the new locations of settlement, which may be near the location of the original climate impact or quite distant. Such distant, indirect effects would compound the direct consequences of climate change at the locations receiving the incoming migrants. In Section 19.5, we discuss other risks newly assessed here, including those arising from ocean acidification. Section 19.6 assesses key risks and vulnerabilities in light of the criteria discussed here (Section 19.2.2) and in the context of the RFCs, and Section 19.7 assesses response strategies aimed at avoiding key risks.

19.2. Framework for Identifying Key Vulnerabilities, Key Risks, and Emergent Risks

19.2.1. Risk and Vulnerability

Definitions and frameworks that systematize hazards, exposure, vulnerability, risk, and adaptation in the context of climate change are multiple, overlapping, and often contested (see, e.g., Burton et al., 1983; Blaikie et al., 1994; Twigg, 2001; Turner et al., 2003a,b; UNISDR, 2004; Schröter, 2005; Adger, 2006; Birkmann, 2006b; Füssel and Klein, 2006; Thomalla et al., 2006; Tol and Yohe, 2006; Villagrán de León, 2006; IPCC, 2007a; Cutter and Finch, 2008; Cutter et al., 2008; ICSU-LAC, 2010a,b; Cardona, 2011; DEFRA, 2012; IPCC, 2012a; Kienberger, 2012; Birkmann et al., 2013a; Costa and Kropp, 2013). Today, key reports and most authors differentiate among hazards, vulnerability, risk, and impacts (see, e.g., Hutton et al., 2011; IPCC, 2012a; Birkmann et al., 2013a). The recent literature underscores that risks from climate change are not solely externally generated circumstances or changes in the climate system to which societies respond, but rather the result of complex interactions among societies or communities, ecosystems, and hazards arising from climate change (Susman et al., 1983; Comfort et al., 1999; Birkmann et al., 2011a, 2013a; UNISDR, 2011; IPCC, 2012a). The differentiation of the various aspects of these interactions is an important improvement since AR4 because it exhibits the social construction of risk through the concept of vulnerability (IPCC, 2012a). This new framework, growing out of SREX, translates information more easily into a risk management approach that facilitates policy making (de Sherbinin, 2013). The following section advances this framework in the context of Article 2 of the UNFCCC.

We refer to the characteristics of climate change and its effects on geophysical systems, such as floods, droughts, deglaciation, sea level rise, increasing temperature, and frequency of heat waves, as *hazards*. In contrast, *vulnerability* refers primarily to characteristics of human or social-ecological systems exposed to hazardous climatic (droughts, floods, etc.) or non-climatic events and trends (increasing temperature, sea level rise) (UNDRO, 1980; Cardona, 1986, 1990; Liverman, 1990; Cannon, 1994, 2006; Blaikie et al., 1996; UNISDR, 2004, 2009; Birkmann, 2006a; Füssel and Klein, 2006; Thywissen, 2006; IPCC, 2012a). Ecosystems or geographic areas can be classified as vulnerable, which is of particular concern if human vulnerability increases as a result of potential impairment of the related ecosystem services. The Millennium Ecosystem Assessment (MEA), for example, identified ecosystem services that affect the vulnerability of societies and communities, such as provision of freshwater resources and air quality (Millennium Ecosystem Assessment, 2005a,b). Examples in this chapter and other chapters in this report include the vulnerability of warmwater coral reefs and respective ecosystem services for coastal communities (see Table 19-4; Box CC-KR).

The new framework used here also underscores that the development process of a society has significant implications for exposure, vulnerability, and risk. Climate change is not a risk per se; rather climate changes and related hazards interact with the evolving vulnerability and exposure of systems and therewith determine the changing level of risk (see Figure 19-1; Table 19-4). Identifying key vulnerabilities facilitates estimating key risks when coupled with information about evolving hazards associated with climate change. This approach provides the basis for criteria developed in the following sections.

19.2.2. Criteria for Identifying Key Vulnerabilities and Key Risks

Vulnerability is dynamic and context specific, determined by human behavior and societal organization, which influences for example the susceptibility of people (e.g., by marginalization) and their coping and adaptive capacities to hazards (see IPCC, 2012a). In this regard coping mainly refers to capacities that allow a system to protect itself in the face of adverse consequences, while adaptation—by contrast—denotes a longer term process that also involves adjustments in the system itself and refers to learning, experimentation, and change (Yohe and Tol, 2002; Pelling, 2010; Birkmann et al., 2013a). Perceptions and cognitive constructs about risks and adaptation options as well as cultural contexts influence adaptive capacities and thus vulnerability (Grothmann and Patt, 2005; Rhomberg, 2009; Kuruppu and Liverman, 2011; see Section 19.6.1.4). SREX stressed that the consideration of multiple dimensions (e.g., social, economic, environmental, institutional, cultural), as well as different causal factors of vulnerability, can improve strategies to reduce risks to climate change (see IPCC 2012c, p. 17; Cardona et al., 2012, pp. 17, 67–106).

Key vulnerability and key risk are defined in Box 19-2. Vulnerabilities that have little influence on overall risk are not considered key. Similarly,

the magnitude or other characteristics of climate change-related hazards, such as glacier melting, sea level rise, or heat waves, are not by themselves adequate to determine key risks, as the consequences of climate change also will be determined by the vulnerability of the exposed society or social-ecological system. Key vulnerabilities and key risks embody a normative component because different societies might rank the various vulnerability and risk factors and actual or potential types of loss and damage differently (see Schneider et al., 2007, p. 785; Lavell et al., 2012, p. 45). Generally, vulnerability merits particular attention when the survival of societies, communities, or ecosystems is threatened (see UNISDR, 2011, 2013; Birkmann et al., 2011a). Climate change will influence the nature of the climatic hazards people and ecosystems are exposed to and also contribute to deterioration or improvement of coping and adaptive capacities of those exposed to these changes. Consequently, many studies (Wisner et al., 2004; Cardona, 2010; Birkmann et al., 2011a) focus with a priority on the vulnerability of humans and societies as a central feature, rather than solely on the level of climatic change and respective hazards.

19.2.2.1. Criteria for Identifying Key Vulnerabilities

We reorganize and further develop criteria for identifying vulnerabilities as "key" used in AR4 based on the literature (Blaikie et al., 1994; Bohle, 2001; Turner et al., 2003a,b; Birkmann, 2006a, 2011a; Villagrán de León, 2006; Cutter et al., 2008; Cutter and Finch, 2008; ICSU-LAC, 2010a,b; Cardona, 2011; UNISDR, 2011; IPCC, 2012a; Birkmann et al., 2013a) and the differentiation of hazard, exposure, and vulnerability presented here. The criteria in this and succeeding sections were used to identify key vulnerabilities, key risks, and emergent risks in Sections 19.4 and 19.6.1-2, and in Table 19-4. Not all of the criteria need to be fulfilled to characterize a vulnerability or risk as key but the characterization of a phenomenon as a KV or key risk is usually supported by more than one criterion.

The following five criteria are used to judge whether vulnerabilities are key:

1) *Exposure of a society, community, or social-ecological system to climatic stressors*. While exposure is distinct from vulnerability, exposure is an important precondition for considering a specific vulnerability as key. If a system is neither at present nor in the future exposed to hazardous climatic trends or events, its vulnerability to such hazards is not relevant in the current context. Exposure can be assessed based on spatial and temporal dimensions.
2) *Importance of the vulnerable system(s). Views on the importance of different aspects of societies or ecosystems can vary across regions and cultures* (see Kienberger, 2012). However, the identification of KVs is less subjective when it involves characteristics that are crucial for the survival of societies or communities or social-ecological systems exposed to climatic hazards. Defining key vulnerabilities in the context of particular societal groups or ecosystem services also takes into account the conditions that make these population groups or ecosystems highly vulnerable, such as processes of social marginalization or the degradation of ecosystems (Leichenko and O'Brien, 2008; O'Brien et al., 2008; IPCC, 2012a).
3) *Limited ability of societies, communities, or social-ecological systems to cope with and to build adaptive capacities to reduce or limit the adverse consequences of climate-related hazard.* Coping and adaptive capacities are part of the formula that determines vulnerability (see IPCC, 2012a; Birkmann et al., 2013a). While coping describes actions taken within existing constraints to protect the current system and institutional settings, adaptation is a continuous process that encompasses learning and change of the system exposed, including changes of rule systems or modes of governance (Smithers and Smit, 1997; Pielke Jr., 1998; Frankhauser et al., 1999; Smit et al., 1999; Kelly and Adger, 2000; Yohe and Tol, 2002; Adger et al., 2005; Smit and Wandel, 2006; Pelling et al., 2008; Pelling, 2010; Tschakert and Dietrich; 2010; IPCC, 2012a; Birkmann et al., 2013a; Garschagen, 2013). Severe limits of coping and adaptation provide criteria for defining a vulnerability as key, as they are core factors that increase vulnerability to climatic hazards (see, e.g., Warner et al., 2012).
4) *Persistence of vulnerable conditions and degree of irreversibility of consequences.* Vulnerabilities are considered key when they are persistent and difficult to alter. This is particularly the case when the susceptibility is high and coping and adaptive capacities are very low as a result of conditions that are hard to change. Irreversible degradation of ecosystems (e.g., warmwater coral reefs), chronic poverty and marginalization, and insecure land tenure arrangements are drivers of vulnerability that in combination with climatic hazards determine risks that often persist over decades (see Box CC-KR), for example, as observed in the Sahel Zone. In this way, communities or social-ecological systems (e.g., coastal communities dependent on fishing or mountain communities dependent on specific soil conditions) may reach a tipping point (or critical threshold) that would cause a partial or full collapse of the system, including displacement (see Renaud et al., 2010; Section 19.4.2.1). Inability to replace such a system or compensate for potential and actual losses and damages (i.e., irreversibility) is a critical criterion for determining what is "key."
5) *Presence of conditions that make societies highly susceptible to cumulative stressors in complex and multiple-interacting systems*. Conditions that make communities or social-ecological systems highly susceptible to the imposition of additional climatic hazards or that impinge on their ability to cope and adapt, such as violent conflicts (e.g., during drought disaster in Somalia (see Menkhaus, 2010)) are considered under this criterion. Also, the critical dependence of societies on highly interdependent infrastructures (e.g., energy/power supply, transport, and health care) (see Rinaldi et al., 2001; Wang, S. et al., 2012; Atzl and Keller, 2013) leads to key vulnerabilities regarding multiple-interacting systems where capacity to cope or adapt to their failure is low (see Copeland, 2005; Reed et al., 2010; Section 19.6.2.1; Table 19-4).

19.2.2.2. Criteria for Identifying Key Risks

Risks are considered "key" due to high hazard or high vulnerability ("key vulnerability") of societies and systems exposed, or both. Criteria for determining key risks build on the criteria for key vulnerabilities, as vulnerability is a component of risk. As such, risk is strongly determined by coping and adaptive capacities. However, the criteria for identifying key risks also take into account the magnitude, frequency, and intensity of hazardous events and trends linked to climate change to which

vulnerable systems are exposed. Accordingly, the following four additional criteria are used to judge whether risks are key:

1) *Magnitude*. Risks are key if associated harmful consequences have a large magnitude, determined by a variety of metrics including human mortality and morbidity, economic loss, losses of cultural importance, and distributional consequences (see Schneider et al., 2007; IPCC, 2012a). Magnitude and frequency of the hazard as well as socioeconomic factors that determine vulnerability and exposure contribute.
2) *Probability that significant risks will materialize and their timing*. Risks are considered key when there is a high probability that the hazard due to climate change will occur under circumstances where societies or social-ecological systems exposed are highly susceptible and have very limited capacities to cope or adapt and consequently potential consequences are severe. Both the timing of the hazard and the dynamics of vulnerability and exposure contribute. Risks that materialize in the near term may be evaluated differently than risks that materialize in the distant future, as the time available for building up adaptive capacities is different (Oppenheimer, 2005; Schneider et al., 2007; see also Section 19.6.3.6).
3) *Irreversibility and persistence of conditions that determine risks*. Persistence of risks refers to the fact that underlying drivers and root causes of these risks, either socioeconomic (e.g., chronic poverty; see Chapter 13) or physical, cannot be rapidly reduced. The criteria for assessing key vulnerabilities include the persistence of socioeconomic conditions contributing to vulnerability that also apply here (Section 19.2.2.1, point 4). In addition, some hazards are associated with the potential for persistent physical impacts, such as loss of an ice sheet causing irreversible sea level rise or release of methane (CH_4) clathrates from the seabed.
4) *Limited ability to reduce the magnitude and frequency or other characteristics of hazardous climatic events and trends and the vulnerability of societies and social-ecological systems exposed*. Criterion 3 pertaining to key vulnerabilities (Section 19.2.2.1) discusses limited ability of societies to improve coping and adaptive capacities in order to manage risk. This criterion also applies here. In addition, risks are also considered to be key when societies together have very limited prospects for reducing the magnitude, frequency, or intensity of the associated climate hazards. For example, risks that may be reduced or limited by greenhouse gas (GHG) reductions that reduce the probability of the associated hazard are less threatening than those for which the likelihood of the hazard cannot be effectively altered (see also Section 19.7.1). For example, risks that are already projected to be large during the next few decades under a range of Representative Concentration Pathways (RCPs) are much more difficult to influence by reducing emissions than those projected to become large late in this century (e.g., see discussion of risk from extreme heat in Section 19.6.3.3).

19.2.3. Criteria for Identifying Emergent Risks

A risk that arises from the interaction of phenomena in a complex system is defined here as an *emergent risk*. For example, feedback processes between climatic change, human interventions involving mitigation and adaptation, and processes in natural systems can be classified as emergent risks if they pose a threat to human security. Emergent risks could arise from unprecedented situations, such as the increasing urbanization of low-lying coastal areas that are exposed to sea level rise or where new pluvial flooding risk emerges due to urbanization of vulnerable areas not historically populated. Some emergent risks have been identified or discussed only recently in the scientific literature, and as a result our ability to assess whether they are key risks is limited. In this chapter, the only emergent risks discussed are those that have the potential to become key risks once sufficient understanding accumulates.

19.2.4. Identifying Key and Emergent Risks under Alternative Development Pathways

Key risks are determined by the interaction of climate-related hazards with exposure and vulnerabilities of societies or ecosystems. Development pathways describing possible trends in demographic, economic, technological, environmental, social, and cultural conditions (Hallegatte et al., 2011) will affect key risks because they influence both the likelihood and nature of climate-related hazards, and the societal and ecological conditions determining exposure and vulnerability. Therefore some risks could be judged to be key under some development pathways but not others. Emergent risks can depend on development pathways as well, because whether or not they become key risks may be contingent on future socioeconomic conditions.

The effect of development pathways on climate-related hazards occurs through their effects on emissions and other radiative forcing factors such as land use change (see WGI AR5 Chapter 12). Components of development pathways such as economic growth, technical change, and policy will influence the rates and spatial distributions of emissions of GHGs and aerosols, and of land use change, and therefore influence the magnitude, timing, and heterogeneity of hazards (see WGIII AR5 Chapter 5).

Development pathways will also influence the factors determining key vulnerabilities of human and ecological systems, including exposure, susceptibility, or sensitivity to impacts, and adaptive capacity (Yohe and Tol, 2002; Füssel and Klein, 2006; Hallegatte et al., 2011; Birkmann et al., 2013a; O'Neill et al., 2014). The magnitude of the aggregate exposure and sensitivity of socio-ecological systems will depend on population growth and spatial distribution, economic development patterns, and social systems. The particular elements of the social-ecological system that are most exposed and sensitive to climate hazards, and that are considered most important, will depend on spatial development patterns as well as on cultural preferences, attitudes toward nature/biodiversity, and reliance on climate-sensitive resources or services, among other factors (Adger, 2006; Füssel, 2009). The degree to which persistent or difficult to reverse vulnerabilities are built into social systems, as well as the degree of inequality in exposure and vulnerability across social groups or regions, also depend on characteristics of development pathways (Adger et al., 2009).

19.2.5. Assessing Key Vulnerabilities and Emergent Risks

The criteria above for assessing vulnerability and risk provide a sequence of potential assessment steps. While the initial assessment phase would

explore whether and how a society or social-ecological system is exposed to climate-related hazards, the assessment would subsequently focus on the predisposition of societies or ecosystems to be adversely affected (vulnerability) and the potential occurrence of severe adverse consequences for humans and social-ecological systems once the hazard interacts with the vulnerability of societies and systems exposed. In addition, the importance of the system at risk and the ability of a society or system to cope and to adapt to these stressors would be assessed. Finally, the application of the criteria would also require the assessment of the irreversibility of the consequences and the persistence of vulnerable conditions. Hence, the assessment criteria for risks focus on the internal conditions of a person, a community (e.g., age structure, poverty), or a social-ecological system and the contextual conditions that influence their vulnerability (e.g., governance conditions and systems of norms), in addition to the assessment of hazards, such as storm intensity, heat waves, and sea level rise, which are directly influenced by climate change. Examples of such KVs and key risks drawn from other chapters of this assessment are provided in Section 19.6 and particularly in Table 19-4 and Box CC-KR.

19.3. Emergent Risk: Multiple Interacting Systems and Stresses

19.3.1. Limitations of Previous Approaches Imply Key Risks Overlooked

Interactions of climate change impacts on one sector with changes in exposure and vulnerability, or with adaptation and mitigation actions affecting the same or a different sector, are generally not included or well integrated into projections of risk (Warren, 2011). However, their consideration leads to the identification of a variety of *emergent risks* that were not previously assessed or recognized. This chapter identifies several such complex system interactions that increase vulnerability and risk synergistically (*high confidence*; Section 19.3). There are a very large number of potential interactions, and many important ones have not yet been quantified, meaning that some key risks have been overlooked (*high confidence*). In some cases, literature analyzing these risks is very recent. The six interaction processes listed below, though not exclusive, are systemic and may lead to further key vulnerabilities as well as a larger number of less significant impacts. Several of these are discussed in more detail in the following sections:

- Biodiversity loss induced by climate change that erodes ecosystem services, in turn increasing vulnerability and exposure of human systems dependent on those services (Section 19.3.2.1).
- Alterations in extreme weather events induced by climate change that affect human systems and ecosystems, increasing vulnerability and exposure to the effects of mean climate change. Most impacts projections are based only on changes in mean climate (Rosenzweig and Hillel, 2008; IPCC, 2012a, Box 3-1).
- The interaction between non-climate stressors such as those related to land management, water management, air pollution (which has drivers in common with climate change), and energy production and climate change (Section 19.3.2.2). Heretofore, mainly climate interactions with population/economic growth were assessed.
- Climate changes that increase human exposure and vulnerability to disease (Section 19.3.2.3).
- Locations where risks in different sectors are compounded because impacts, hazards, vulnerability, and exposure interact non-additively (Section 19.3.2.4).
- Mitigation or sectoral adaptation that has unintended consequences for the functioning of another sector (Section 14.6).

19.3.2. Examples of Emergent Risks

19.3.2.1. Emergent Risks Arising from the Effects of Degradation of Ecosystem Services by Climate Change

Biodiversity loss is linked to disruption of ecosystem structure, function, and services (Díaz et al., 2006; Gaston and Fuller, 2008; Cardinale et al., 2012; Maestre et al., 2012; Midgley, 2012). Terrestrial and freshwater species face increased extinction risks under projected climate change during and beyond the 21st century, especially as climate change interacts with other pressures (*high confidence*; Section 4.3.2.5). A large number of modelling studies project that species ranges decline in size as mean climate changes (Section 4.3.2.5); for example, a global scale study of 50,000 species found that the range sizes of 57 ± 6% of widespread and common plants and 34 ± 7% of widespread and common animals are projected to decline by more than 50% by the 2080s if global temperatures increase by 3.5°C relative to preindustrial times, when allowing for species to disperse at observed rates to areas that become newly climatically suitable (Warren et al., 2013a). AR4 (Fischlin et al., 2007, p. 213) estimated that "Approximately 20 to 30% of plant and animal species assessed so far (in an unbiased sample) are likely to be at increasingly high risk of extinction as global mean temperatures exceed a warming of 2 to 3°C above preindustrial levels (*medium confidence*)." Evaluation of various lines of evidence including a range of modeling approaches and, since AR4, new and/or improved techniques (e.g., multifactorial driven species distribution models, species specific population dynamics, tree- and trait-based modeling (for an overview see Bellard et al., 2012, Table 1; also Murray et al., 2011; Dullinger et al., 2012; Staudinger et al., 2012; Foden et al., 2013) imply similar levels of risk as in AR4 with some new estimates indicating higher fractions of species at risk. However, there is *low agreement* on the completeness of these lines of evidence for assigning specific numerical values for fraction of species at risk (see Sections 4.3.2.5, 19.5.1).

These extinction risks and possible declines in species richness are associated with change in mean climate, but ecosystems and species are also expected to be affected by projected climate change-induced increases in short-term extreme weather events and increased fire frequency in some locations (see IPCC, 2012a; WGI AR5 Table SPM.1; WGI AR5 Sections 6.4.8.1, 12.4.3, 12.4.5). Accordingly, despite the recognition of additional uncertainties in numerical estimates since AR4 (Section 4.3.2.5), the evidence for risk to a substantial fraction of species associated with increasing global mean temperature (GMT) is *robust*.

In both terrestrial and marine environments, the potential for the disruption of ecosystem functionality as a result of climate change translates into a key risk of large-scale loss of ecosystem services (Mooney et al., 2009; Midgley, 2012; Table 19-4). At-risk services include water purification by wetlands, removal and sequestration of carbon dioxide (CO_2) by forests, crop pollination by insects, coastal protection

by mangroves and coral reefs, regulation of pests and disease, and recycling of waste nutrients (Sections 4.3.4, 22.4.5.6, 27.3.2.1; Box 23-1; Chivian and Bernstein, 2008). Biodiversity loss can lead to an increase in the transmission of infectious diseases such as Lyme, schistosomiasis, and hantavirus in humans, and West Nile virus in birds, creating a newly identified dimension to the emergent risks resulting from biodiversity loss (Keesing et al., 2010).

There are a number of examples of projected yield losses in the agricultural sector due to increased prevalence of pest species under climate change including *Fusarium graminearum* (a fungal disease of wheat), the European corn borer, the Colorado beetle, bakanae disease and leaf blights of rice, and Western corn root worm (Petzoldt and Seaman, 2006; Huang et al., 2010; Kocmánková et al., 2010; Chakraborty and Newton, 2011; Magan et al., 2011; Aragón and Lobo, 2012); or declines in pollinators (Rosenzweig and Hillel, 2008; Abrol, 2012; Bedford et al., 2012; Giannini et al., 2012; Kuhlmann et al., 2012; see also Section 4.3.4). Climate change impacts on pollinators places these valuable services at risk, and affects animals that are dependent on the plants (see Chapter 4). Although the impacts of CO_2 fertilization on plant-pathogen systems is not well understood (Section 7.3.2.3), these processes operate simultaneously with climate change's direct effects on yields through changing temperature, precipitation, and CO_2 concentrations, creating an emergent risk. Climate change has caused, or is projected to cause, range expansion in weeds that have the potential to become invasive (Bradley et al., 2010; Clements and Ditommaso, 2011). These can damage agriculture and threaten other species with extinction, with costs to economies being extremely high (e.g., US$120 billion annually in the USA; Pimentel et al., 2005; Crowl et al., 2008). Although there are also examples of projected decreases in insect damage to crops, there is a tendency for risk of insect damage to plants to increase with climate change (Section 7.3.2.3). Any one of the above mechanisms could result in harmful outcomes that act in synergy with existing climate change impacts on agriculture. Hence, these various susceptibilities to loss of ecosystem services comprise a KV and, in interaction with climate change, imply a potential key risk that global scale yields of a number of crops will be reduced by such interactions.

Severe decline of coral reefs (Section 19.3.2.4) would result in widespread loss of income for many countries, for example, AU$5.4 billion to the Australian economy from tourism (Box CC-CR). More generally, for many small island developing states (SIDS), increases in vulnerability due to loss of such ecosystem services interact with physical impacts of climate change such as sea level rise to create an emergent risk (*high confidence*).

Various studies of ecosystem services, nationally or globally, illustrate the very large values that are attributed to these services (Table 19-1). Such costs are represented only very crudely in aggregate global models of the economic impacts of climate change where "non-market impacts" are estimated very broadly if at all (Section 19.6.3.5). These costs contribute to the large magnitude of risks to human systems resulting from loss of ecosystem services, which in some cases would be irreversible. Hence the increase in vulnerability due to loss of ecosystem services interacting with climate change hazards comprises a key risk (*high confidence*). In some regions (e.g., South America) payment for ecosystem services (PES) has been implemented to support landowners to maintain the provision of services over time (Section 27.6.2; Table 27-7). Studies on degraded ecosystems examine the cost of restoring ecosystem services. Willingness to pay to restore degraded services along the Platte River (USA) (Loomis et al., 2000) greatly exceeded estimated costs of restoration. A meta-analysis of 89 studies looking at the restoration of ecosystem services measured using 526 different metrics found that restoration increased the amount of biodiversity and ecosystem services by 44 and 25% respectively, but restored services were still lower than in intact ecosystems (Benayas et al., 2009). Restoration of damaged ecosystems may be cost-effective, but only partially compensates for loss of services.

Concomitant stress from land use change adds to the extinction risk from climate change, increasing the projected extinction rate (e.g., Şekercioğlu et al., 2012) and contributing to the emergent risk of ecosystem service loss (see also Chapter 4). A synthesis of empirical studies across the globe reveals that ecosystem impacts due to land use change correlate locally with current maximum temperature and recent precipitation decline, indicating a potential for climate change to exacerbate the impacts of land use change (Mantyka-Pringle et al., 2012).

Land clearing releases carbon to the atmosphere and removes carbon sinks (WGI AR5 Section 6.3.2.2) such as old growth forests which would otherwise accumulate carbon (Luyssaert et al., 2008). Studies that value ecosystem services have tended to underestimate the importance of carbon sinks in ecosystems, owing to a tendency to consider only the carbon currently stored in the systems and not the fluxes (Anderson-Teixeira and DeLucia, 2011) and overlooking other aspects such as changes in albedo (e.g., Betts et al., 2012).

19.3.2.2. Emergent Risk Involving Non-Climate Stressors: The Management of Water, Land, and Energy

Human management of water, land, and energy interacts with climate change and its impacts, to profoundly affect risks to the amount of

Table 19-1 | Examples of global and national ecosystem service valuation studies. This table is not intended to be comprehensive. Furthermore, it encompasses studies based on a wide range of methodologies.

Ecosystem service	Region	Value	Currency	Citation
Pollination of crops	Globe	153 billion	Euro	Gallai et al. (2009)
Pollination of crops and wild plants	UK	430 million	£	UK NEA (2011)
Woodland cover increase from 6 to 12%	UK	680 million	£	UK NEA (2011)
CO_2 fixation, O_2 release, nutrient recycling, soil protection, water holding capacity, and environmental purification	Chinese terrestrial ecosystems	6.6 trillion	Yuan RMB	Shi et al. (2012)
Climate regulation provided by forests	USA	1–6 billion	US$ per year	Krieger (2001)
Recreation provided by forests	USA	1.3–110 billion	US$ per year	Krieger (2001)
Biodiversity supported by forests	USA	554 billion	US$ per year	Krieger (2001)
Coral reef services	Australia	5.4 billion	Au$	Section 19.3.2.1; Box CC-CR

carbon that can be stored in terrestrial ecosystems, the amount of water available for use by humans and ecosystems, and the viability of adaptation plans for cities or protected areas. Failure to manage land, water, and energy in a synergistic fashion can exacerbate climate change impacts globally (Searchinger et al., 2008; Wise et al., 2009; Lotze-Campen et al., 2010; Warren et al., 2011) producing emergent risks which are also potential key risks. For example, the use of water by the energy sector, by thermo-electric power generation, hydropower, and geothermal energy, or biofuel production, can contribute to water stress in arid regions (Kelic et al., 2009; Pittock, 2011). Some energy technologies (biofuels, hydropower, thermal power plants), transportation fuels and modes, and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops) require more water than others (Box CC-WE; Sections 3.7.2, 7.3.2, 10.2, 10.3.5; McMahon and Price, 2011; Macknick et al., 2012; Ackerman and Fisher, 2013). In irrigated agriculture, climate, crop choice, and yields determine water requirements per unit of produced crop, and in areas where water must be pumped or treated, energy must be provided (Box CC-WE; Gerten et al., 2011). Recent studies address the energy, water, and land "nexus" to explore risks to the agricultural and energy sectors (Box CC-WE; Tidwell et al., 2011; Skaggs et al., 2012; Smith et al., 2013).

Biofuels can potentially mitigate GHG emissions when used in place of fossil fuels such as gasoline, diesel, and more carbon-intensive fuels from tar sands and heavy oil (Cherubini et al., 2009). One simulation of stringent mitigation (e.g., RCP2.6, which constrains radiative forcing to 2.6 W m^{-2} and therefore limits global mean temperature increase to 2°C over preindustrial levels during the 21st century) shows an increased reliance on biofuels (van Vuuren et al., 2011). However, due to the potential negative consequences of its use as a mitigation strategy, bioenergy development leads to several emergent risks, which are summarized in Table 19-2. Systems that may be vulnerable to bioenergy development are food systems (*high confidence*, due to bioenergy feedstocks replacing food crops; see Table 19-2.iii; Section 19.4.1) and ecosystems (*high confidence*), where biofuel cropping can directly or indirectly induce land use change, displacing terrestrial ecosystems such as forests, which can otherwise also act as carbon sinks (see Table 19-2.i).

While *direct* land use change (LUC) from impacts of biofuel development (from crop substitution and/or biofuel feedstock crop expansion) are a concern, *indirect* land use change (iLUC) has received more attention in the literature—both due to the magnitude of its potential impact (twice as great as direct LUC; Melillo et al., 2009a) and controversy over the uncertainty in accurately quantifying it. iLUC connotes land use change resulting from biofuel impacts on agricultural commodity markets (Fargione et al., 2008; Searchinger et al., 2008). Reductions of GHG emissions from biofuel production and use (compared to fossil fuels) may be offset partly or entirely for decades or centuries from iLUC-induced CO_2 emissions from deforestation and the draining of peatlands (*medium confidence*; Bringezu et al., 2009; van Vuuren et al., 2010; IPCC, 2011, Chapter 2; Miettinen et al., 2012; Smith et al. 2013). In Brazil, further biofuel expansion would be expected to impinge upon the Cerrado, the Amazon, and the Atlantic rainforest—all three of which have high levels of biodiversity (Table 19-2.v) and high levels of endemism (Lapola et al., 2010). Another study of biofuel production in Brazil (Barr et al., 2011) found that when pasture is accounted for, direct expansion into unexploited forest land is minor, that is, most of additional cropland is predicted to come from conversion of pastureland. However, unless the density of livestock operations is increased in tandem, the latter can also lead to iLUC. To the extent that biofuel feedstock crops are grown on areas that were previously fallow or degraded, the iLUC effects might be minimized and CO_2 potentially sequestered (Fargione et al., 2010; IPCC, 2011)—although the amount, alternative uses, and potential productivity of so-called degraded lands are still contested (Dauber et al., 2012). (For more information on the effects of biofuel production on terrestrial ecosystems, see Section 4.4.4; for more information on the effects of land acquisition for biofuel production on the poor, see Section 13.3.1.4.)

Whether such land management dynamics confound or contribute to mitigation depends on important interactions with global emissions mitigation policies (Table 19-2.ii; Van Vuuren et al., 2011). A failure to include land use change emissions within a carbon mitigation regime—for example, by applying a carbon price to fossil fuel and industrial emissions only—has been projected to lead to large-scale deforestation of natural forests and conversion of many other natural ecosystems by the end of the 21st century in 450 ppmv CO_2-eq and 550 ppmv CO_2-eq scenarios (Melillo et al. 2009b; Wise et al., 2009). This dynamic is due primarily to enhanced bioenergy production without a corresponding incentive to limit the resulting land use change emissions. If, instead, an equal carbon price is applied to terrestrial carbon (which, however, presents monitoring difficulties) along with fossil and industrial carbon, deforestation could slow down or even reverse.

That said, there are many equally compelling reasons for a country to encourage biofuel production including a means to produce downward pressure on oil prices, rural development, and reduced oil imports—all of which could be prioritized over biofuels as a GHG mitigation strategy depending on the country (Cherubini et al., 2009). Per-liter GHG emissions from biofuels decrease as agriculture is further intensified through row cropping, fertilizer and pesticide use, and irrigation, while other per-liter environmental impacts such as eutrophication increase (Burney et al., 2010; Grassini and Cassman, 2012). This creates an implicit conflict between alternative development priorities. Second-generation biofuels, such as those based on non-food crops (grasses, algae, timber) and agricultural residues, are expected to offer reduced emissions of GHGs and other air pollutants compared to most first-generation biofuels. This is due primarily to their having a smaller adverse interaction with food systems resulting in less LUC and iLUC (Plevin, 2009; Cherubini and Ulgiati, 2010; Fargione, 2010; Sander and Murthy, 2010). Further, bioelectricity and biogas both may be more effective at mitigating GHG emissions than liquid biofuels (Campbell et al., 2009; Power and Murphy, 2009).

Other emergent risks from bioenergy development are summarized in Table 19-2. Nearly all of the risks presented here are driven by the increased need for raw agricultural feedstocks. Competition for cultivable lands, irrigation resources (Box CC-WE), and other inputs are not unique to biofuel-related issues. The approximate doubling of agricultural demand projected between 2005 and 2050 (Tilman et al., 2011) similarly increases competition for land and water, and would be expected to exacerbate GHG emissions from agriculture (see also WGI AR5 Sections 6.4.3.2, 8.3.5).

Table 19-2 | Emergent risks related to biofuel production as a mitigation strategy.

No.	Issue	Issue description	Nature of emergent risk	Reference
i	Direct and/or indirect land use change	Potential for enhancement of greenhouse gas emissions	Mitigation benefit of biofuels reduced or negated	Melillo et al. (2009a,b); Wise et al. (2009); Khanna et al. (2011)
ii	Policies targeting only fossil carbon	Biofuel cropping competes with agricultural systems and ecosystems for land and water.	Mitigation benefit of policies reduced; harmful interactions with other key systems	Searchinger et al. (2008); Mellilo et al. (2009a,b); Wise et al. (2009); Fargione et al. (2008)
iii	Food/fuel competition for land	Competition for land driving up food prices	Emergent risk of food insecurity due to mitigation-driven land use change	Searchinger et al. (2008); Pimentel et al. (2009); Hertel et al. (2010)
iv	Biofuel production affects water resources.	Competition for water affects biodiversity and food cropping.	Emergent risk of biodiversity loss and food insecurity due to mitigation-driven water stress	Fargione (2010); Fingerman et al. (2010); Poudel et al. (2012); Yang et al. (2012)
v	Biofuel production affects biodiversity.	Competition for land reduces natural forest and biodiversity.	Emerging risk of biodiversity loss due to mitigation-driven land use change	Fizherbert et al. (2008); Koh et al. (2009); Lapola et al. (2010); Fletcher et al. (2011)
vi	Land conversion causes air pollution.	Potential for increased production of tropospheric ozone from palm/sugarcane-induced land use change	Emergent risk of greenhouse gas-mitigation-driven plant and human health damage caused by tropospheric ozone	Cançado et al. (2006); Hewitt et al. (2009)
vii	Fertilizer application	Potential for increased emissions of N_2O	Offsets some benefits of other mitigation measures	Donner and Kucharik (2008); Searchinger et al. (2008); Fargione (2010)
viii	Invasive properties of biofuel crops	Potential to become an invasive species	Unintended consequences that damage agriculture and/or biodiversity	Raghu et al. (2006); DiTomaso et al. (2007); Barney and Ditomaso (2008)

Projected changes in the hydrological cycle due to climate change (WGI AR5 Section 12.4.5) combined with increasing water demand leads to an emergent, potentially key risk of water stress exacerbated by the reduction of groundwater which serves as "an historical buffer against climate variability" (Green et al., 2011), and potentially further exacerbated by existing governance constraints that can act as barriers to reduce vulnerability. Climate change and increasing food demand are expected to drive expansion of irrigated cropland (Wada et al., 2013), increasing the demand for energy intensive extraction and conveyance of (ground or desalinated sea) water for irrigation (see Box CC-WE). If water is provided through groundwater extraction, pumping, or construction and use of de-salinization plants, local energy demand (and GHG emissions) will increase, although advanced irrigation systems are available that minimize enhancement of emissions (Rothausen and Conway, 2011).

A further potential key risk arises from increased water stress due to unsustainable groundwater extraction, which is expected to increase as an adaptation to climate change. Groundwater extraction is generally increasing globally with particularly large extraction in India and China (Wang, J. et al., 2012). The effects of climate change on groundwater are varied with some areas expecting decreased recharge while others are projected to experience increased recharge (Green et al., 2011; Portmann et al., 2013). Where extraction rates increase or recharge decreases, water tables will be depleted with potential key risks to local ecosystems and human systems (such as agriculture, tourism, and recreation), while water quality will decrease. One projection shows insufficient water availability in Africa, Latin America, and the Caribbean to satisfy both agricultural demands and ideal environmental flow regulations for rivers by 2050, a situation that is exacerbated by climate change (Strzepek and Boehlert, 2010).

19.3.2.3. Emergent Risks Involving Health Effects

Climate change will act through numerous direct and indirect pathways to alter the prevalence and distribution of diseases that are climate and weather sensitive. These effects will differ substantially depending on baseline epidemiologic profiles, reflecting the level of development and access to clean and plentiful water, food, and adequate sanitation and health care resources. Furthermore, the impact of climate change will differ within and between regions, depending on the adaptive capacity of public health and medical services and key infrastructure that ensures access to clean food and water.

A principal emergent global public health risk is malnutrition secondary to ecological changes and disruptions in food production as a result of changing rainfall patterns, increases in extreme temperatures (*high confidence*; IPCC, 2012a; see also Section 11.6.1), and increased atmospheric CO_2 (Taub et al., 2008; Burke and Lobell, 2010; Section 7.3.2.5). Modeling of the magnitude of the effect of climate change on future under-nutrition in five regions in South Asia and sub-Saharan Africa in 2050 (using *Special Report on Emissions Scenarios* (SRES) A2 emissions scenario) suggests an increase in moderate nutritional stunting, an indicator linked to increased risk of death and poor health (Black et al., 2008), of 1 to 29%, depending of the region assessed, compared to a future without climate change, and a much greater impact on severe stunting for particular regions, such as 23% for central sub-Saharan Africa and 62% for south Asia (Lloyd et al., 2011). The impact of climate-induced drought and precipitation changes in Mali include the southward movement of drought-prone areas which would result in a loss of critical agriculturally productive land by 2025 and increase food insecurity (Jankowska et al., 2012).

In densely populated megacities, especially those with a pronounced urban heat island effect, a principal emergent health risk results from the synergistic interaction between increased exposure to extreme heat and degraded air quality with the convergence of increasing vulnerability of an aging population and a global shift to urbanization (*high confidence*; Sections 8.2.3.5, 8.2.4.6, 11.5.3; Box CC-HS). These trends will increase the risk of relatively higher mortality from exposure to excessive heat (Knowlton et al., 2007; Kovats and Hajat, 2008; Luber and McGeehin, 2008). The health risks of such interactions include increased injuries and fatalities as a result of severe weather events including heat waves (see Section 19.6.3.3); increased aeroallergen production in urban areas leading to increases in allergic airway diseases

(see Section 19.5.3); and respiratory and cardiovascular morbidity and mortality secondary to degraded air quality and ozone formation (see Section 19.6.3.3). While the association between ambient air quality and health is well established, there is an increasingly *robust* body of evidence linking spikes in respiratory diseases to weather events and to climate change. In New York City, for example, each single degree (Celsius) increase in summertime surface temperature has been associated with a 2.7–3.1% increase in same-day hospitalizations due to respiratory diseases, and an increase of 1.4–3.6% in hospitalizations due to cardiovascular diseases (Lin et al., 2009). Respiratory health outcomes will be exacerbated by climate change through increased production and exposure to ground-level ozone (particularly in urban areas), wildfire smoke, and increased production of pollen (D'Amato et al., 2010).

19.3.2.4. Spatial Convergence of Multiple Impacts: Areas of Compound Risk

In this chapter, we define an area of compound risk as a region where climate change-induced impacts in one sector affects other sectors in the same region, or a region where climate change impacts in different sectors are compounded, resulting in extreme or high-risk consequences. The frequent and ongoing spatial and temporal coincidence of impacts in different sectors in the same region has consequences that are more serious than simple summation of the sectoral impacts indicates (*medium confidence*). Such synergistic processes are difficult to identify through sectoral assessment and are apt to be overlooked in spite of their potential importance in considering key vulnerabilities and risks. For example, a large flood in a rural area may damage crop fields severely, causing food shortages (Stover and Vinck, 2008). The flood may simultaneously cause a deterioration of hygiene in the region and the spread of water-borne diseases (Schnitzler et al., 2007; Hashizume et al., 2008; Kovats and Akhtar, 2008). The coincidence of disease and malnutrition can thus create an area of compound risk for health impacts, with the elderly and children most at risk.

As a systematic approach, identification of areas of compound risk could be achieved by overlaying spatial data of impacts in multiple sectors, but this cannot indicate synergistic influences and dynamic changes in these influences quantitatively. For global analysis, certain types of integrated assessment models that allow spatial analysis of climate change impacts have been used to identify regions that are affected disproportionately by climate change (MNP, 2006; Kainuma et al., 2007; Warren et al., 2008; Füssel, 2010). Recent efforts attempt to collect and archive spatial data on impact projections and facilitate their public use. These have created overlays for identifying areas of compound risk with Web-Geographic Information Systems (GIS) technology (Adaptation Atlas; Resources for the Future, 2009). There are also efforts to coordinate impacts assessments adopting identical future climatic and/or socioeconomic scenarios at various spatial scales (Parry et al., 2004; Piontek et al., 2014). Areas of compound risk identified by overlaying spatial data of impacts in multiple sectors can be used as a starting point for regional case studies on vulnerability and multifaceted adaptation strategies (Piontek et al., 2014).

Frequently Asked Questions

FAQ 19.2 | How does climate change interact with and amplify preexisting risks?

There are two components of risk: the probability of adverse events occurring and the impact or consequences of those events. Climate change increases the probability of several types of harmful events that societies and ecosystems already face, as well as the associated risks. For example, people in many regions have long faced threats associated with weather-related events such as extreme temperatures and heavy precipitation (which can trigger flooding). Climate change will increase the likelihood of these two types of extremes as well as others. Climate change means that impacts already affecting coastal areas, such as erosion and loss of property in damaging storms, will become more extensive due to sea level rise. In many areas, climate change increases the already high risks to people living in poverty or to people suffering from food insecurity or inadequate water supplies. Finally, climate and weather already pose risks for a wide range of economic sectors, including agriculture, fisheries, and forestry: climate change increases these risks for much of the world.

Climate change can amplify risks in many ways, including through indirect interactions with other risks. These are often not considered in projections of climate change impacts. For example, hotter weather contributes to increased amounts of ground level ozone (smog) in polluted areas, exacerbating an existing threat to human health, particularly for the elderly and the very young and those already in poor health. Also, efforts to mitigate or adapt to climate change can have negative as well as positive effects. For example, government policies encouraging expansion of biofuel production from maize have recently contributed to higher food prices for many, increasing food insecurity for populations already at risk, and threatening the livelihoods of those like the urban poor who are struggling with the inherent risks of poverty. Increased tapping of water resources for crop irrigation in one region in response to water shortages related to climate change can increase risks to adjacent areas that share those water resources. Climate change impacts can also reverberate by damaging critical infrastructure such as power generation, transportation, or health care systems.

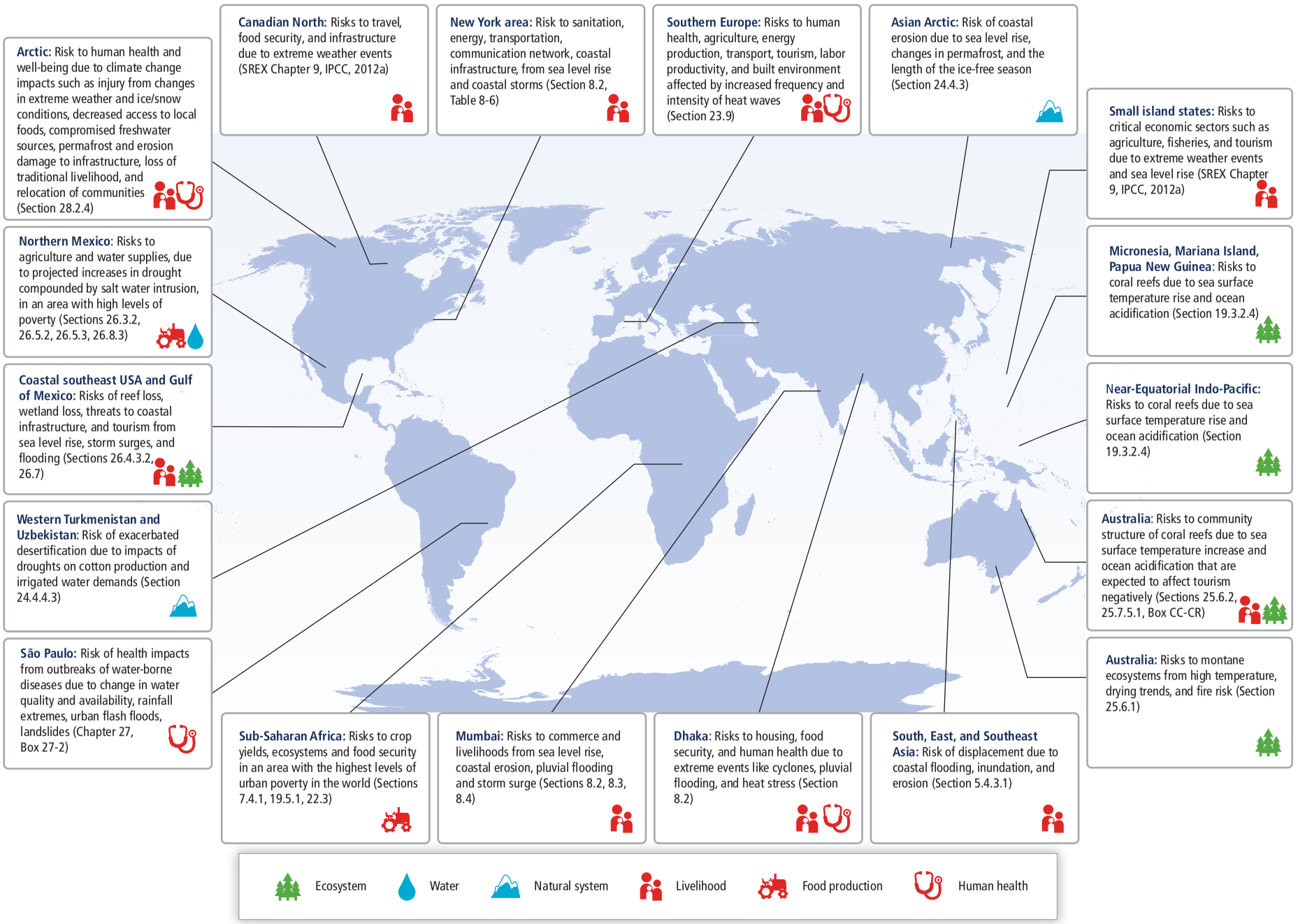


Figure 19-2 | Some examples of areas of compound risk identified in this assessment. Symbols indicate one or two of the main sectors or systems subject to compound risk, but in each case additional sectors and systems are at risk.

General equilibrium economic models (see Chapter 10) may facilitate quantitative evaluation of synergistic influences. An analysis of the EU by the PESETA project (Projections of economic impacts of climate change in sectors of Europe based on bottom-up analysis) showed sub-regional welfare loss by considering impacts on agriculture, coastal system, river floods, and tourism together in the Computable General Equilibrium (CGE) model, which is designed to represent interrelationships among economic activities of sectors. The result indicated the largest percentage loss in southern Europe (Ciscar et al., 2011).

The following examples illustrate different types of areas of compound risk where climate change impacts coincide and interact:

1) *Cities in deltas*, which are subject to sea level rise, storm surge, coastal erosion, saline intrusion, and flooding. Extreme weather events can also disrupt access to food supplies, enhancing malnutrition risk (Ahmed et al., 2009; see also Section 19.3.2.3). Based on national population projections, if contemporary rates of effective sea level rise (a net rate, defined by the combination of eustatic sea level rise and local contributions from fluvial sediment deposition and subsidence and subsidence due to groundwater and hydrocarbon extraction) continue through 2050, more than 6 million people would be at risk of enhanced inundation and increased coastal erosion in three megadeltas and 8.7 million in 40 deltas, absent measures to adapt (Ericson et al., 2006). Examples of urbanized delta areas at risk include, for example, those where Mumbai and Dhaka are located (see Chapters 8, 24; Section 19.6.3.4; Table 19-4).
2) *The Arctic*, where indigenous people (Crowley, 2011) are projected to be exposed to the disruption, and possible destruction of, their hunting and food sharing culture (see Chapter 28). Risk arises from a combination of sea ice loss and the concomitant local extinctions of the animals dependent on the ice (Johannessen and Miles, 2011). Thawing ground also disrupts land transportation, buildings, and infrastructure while exposure of coastal settlements to storms also increases due to loss of sea ice. Arctic ecosystems are broadly at risk (Kittel et al., 2011).
3) *Coral reefs*, which are highly threatened due to the synergistic effects of sea surface temperature rise and perturbed ocean chemistry, reducing calcification and also increasing sensitivity to other impacts such as the loss of coral symbionts (Chapter 6). The importance of reef sensitivity to climate change was recently highlighted in the near-equatorial Indo Pacific, the area of greatest reef diversity worldwide (Lough, 2012). A second highly diverse reef system at risk for warming was identified around Micronesia, Mariana Island, and Papua New Guinea (Meissner et al., 2012).

In Figure 19-2, these and other examples of areas of compound risk identified in this assessment are indicated on a world map. The map focuses on the key role that exposure plays in determining risk, particularly compound risk, rather than vulnerabilities per se.

19.4. Emergent Risk: Indirect, Trans-boundary, and Long-Distance Impacts

Climate change impacts can have consequences beyond the regions in which they occur. Global trade systems transmit and mediate a variety of impacts—the most prominent example of this is the global food trade system. The competitive market forces which dominate trade do not account for considerations of justice, and thus can incidentally diminish or enhance inequality in the distribution of impacts (see Section 19.6.3.4). Where prices on food, land, and other resources increase, vulnerability increases, *ceteris paribus*, for those most in need and least able to pay (see Section 19.6.1.2 on differential vulnerability). In addition, both mitigation and other adaptation responses have unintended consequences beyond the locations in which they are implemented (Oppenheimer, 2013). All of these mechanisms can create emergent risks (*high confidence*).

19.4.1. Crop Production, Prices, and Risk of Increased Food Insecurity

Recent literature indicates that climate trends have already influenced the yield trends of important crops (e.g., Kucharik and Serbin, 2008; Tao et al., 2008; Brisson et al., 2010; Lobell et al., 2011). Chapters 7 and 18 provide a detailed overview of these impacts, and have assessed with *medium confidence* that the effects of climate trends on maize and wheat yield trends have been negative in many regions over the past several decades, and have been small for major rice and soybean production areas (see Sections 7.2.1.1, 18.4.1.1.). For projected impacts, "Without adaptation, local temperature increases in excess of about 1°C above preindustrial is projected to have negative effects on yields for the major crops (wheat, rice, and maize) in both tropical and temperate regions, although individual locations may benefit (*medium confidence*)" (Section 7.4; Figures 7-4, 7-5, 7-7; Chapter 7 ES). Across all studies projecting crop yield impacts (some of which include both CO_2 fertilization and adaptation, and some which account for only one or neither of these), negative impacts on average yields become *likely* from the 2030s (Figure 7-5). Median yield impacts of 0 to –2% per decade are projected for the rest of the century (compared to yields without climate change) (Figure 7-7), and after 2050 the risk of more severe impacts increases (*medium confidence*) (Chapter 7 ES; Figure 7-5). Among the smaller number of studies that have projected global yield and price impacts, negative net effects of climate change, CO_2 increases, and agronomic adaptation on global yields are *about as likely as not* by 2050 and *likely* later in the 21st century (Section 7.4.4).

Climate impacts on crop production influence food prices directly and through complex interactions with a variety of factors, including biofuel crop production and mandates, as well as other domestic policies such as crop export bans (Sections 7.1.2, 7.2.2, 7.4.4). If climate changes reduce crop yields, international food prices and the number of food-insecure people are expected to increase globally (*limited evidence*, *high agreement*; Section 7.4.4). For example, global rice prices exhibit sensitivity both to yield impacts from climate changes as well as the loss of arable land to sea level rise (Chen et al., 2012). While the evidence base of how climate change will affect future food consumption patterns is limited (Section 7.3.3.2), there are large numbers of households that would be especially vulnerable to a loss of food access if food prices were to increase, for example, agricultural producers in low-income countries who are net food buyers (Section 7.3.3.2; Table 7-1).

In addition to the direct impacts of climate change, biofuel production in service of climate change mitigation may also affect food prices.

Accurately tracking and quantifying the direct and indirect impacts of biofuel production on the food system has become an intense area of study since AR4. U.S. ethanol production (for which maize is the primary feedstock) increased around 720% since 2000, with maize commodity prices nearly tripling and harvested land growing by more than 10%, mainly at the expense of soy (Wallander et al., 2011; EIA, 2013). Ethanol recently consumed one-quarter of U.S. maize production, even after accounting for feed by-products returned to the market (USDA, 2013). However, isolating biofuels' exact contribution to food system changes from other factors such as extreme weather events, climate change, changing diets, and increasing population have proven difficult (Zilberman et al., 2011). Still, estimates of the supply and demand elasticity of basic grain commodities lead to a prediction that the 2009 U.S. Renewable Fuel standard could increase commodity prices of maize, wheat, rice, and soybeans by roughly 20%, *ceteris paribus*, assuming one-third of the calories used in ethanol production can be recycled as animal feed (Roberts and Schlenker, 2013). More generally, there is *high confidence* that pressure on land use for biofuels will further increase food prices (see Table 19-2.iii).

In summary, through the global food trade system, climate change impacts on agriculture can have consequences beyond the regions in which those impacts are directly felt. Food access can be inhibited by rising food price levels and volatility (Sections 7.3.3.1-2), as demonstrated during the recent 2007–2008 price rise episode that resulted from the combination of poor weather in certain world regions combined with a demand for biofuel feedstocks, increased demand for grain-fed meat, and historically low levels of food stocks (Abbot and Borot de Battisti, 2011; Adam and Ajakaiye, 2011; Figure 7-3). These episodes provide an analog elucidating how reduced crop yields due to impacts of climate variability and biofuel cropping work synergistically to create a risk of increased food insecurity: hence this interaction of climate change and mitigation actions with the food system via markets comprises an *emergent risk* of the impacts of climate change acting at a distance, affecting the food security of vulnerable households (Section 7.3.3.2).

19.4.2. Indirect, Trans-boundary, and Long-Distance Impacts of Adaptation

Risk can also arise from unintended consequences of adaptation (see Section 14.6), and this can act across distance, if for example, there is migration of people or species from one region to another. Adaptation responses in human systems can include land use change, which can have both trans-boundary and long-distance effects, and changes in water management, which often has downstream consequences.

19.4.2.1. Risks Associated with Human Migration and Displacement

Human migration is one of many possible adaptive strategies or responses to climate change (Reuveny, 2007; Tacoli, 2009; Piguet, 2010; McLeman, 2011), assessed in detail in Chapter 12 in the context of the many other causes of migration. Displacement refers to situations where choices are limited and movement is more or less compelled by land loss due to sea level rise or extreme drought, for example (see Section 12.4). A number of studies have linked past climate variability to both local and long-distance migration (see review by Lilleør and Van den Broeck, 2011). In addition to yielding positive and negative outcomes for the migrants, migration indirectly transmits consequences of climate variability and change at one location to people and states in the regions receiving migrants, sometimes at long distances. Consequences for receiving regions, which can be assessed by a variety of metrics, could be both positive and negative, as may also be the case for sending regions (Foresight, 2011; McLeman, 2011; see Chapter 12). A rapidly growing literature examines potential changes in migration patterns due to future climate changes, but projections of specific positive or negative outcomes are not available. Furthermore, recent literature underscores risks previously ignored: risks arising from the lack of mobility in face of a changing climate, and risks entailed by those migrating into areas of direct climate-related risk, such as low-lying coastal deltas (Foresight, 2011; see Section 12.4.1.2).

Climate change-induced sea level rise, in conjunction with storm surges and flooding, creates a threat of temporary and eventually permanent displacement from low-lying coastal areas, the latter particularly the case for small island developing states (SIDS) and other small islands (Pelling and Uitto 2001; see Chapter 12). The distance and permanence of the displacement will depend on whether governments develop strategies such as relocating people from highly vulnerable to less vulnerable areas nearby, and conserving ecosystem services which provide storm surge protection in addition to so-called "hardening" including building sea walls and surge barriers (Perch-Nielsen, 2004; Box CC-EA). Numbers of people at risk from coastal land loss have been estimated on a regional basis (Ericson et al., 2006; Nicholls and Tol, 2006; Nicholls et al., 2011) yet projections of resulting anticipatory migration or permanent versus temporary displacement are not available.

Taken together, these studies indicate that climate change will bear significant consequences for migration flows at particular times and places, creating risks as well as benefits for migrants and for sending and receiving regions and states (*high confidence*). Urbanization is a pervasive aspect of recent migration which brings benefits but, in the climate change context, also significant risks (see Sections 8.2.2.4, 19.2.3, 19.6.1-2, 19.6.3.3). While the literature projecting climate-driven migration has grown recently (Section 12.4), there is as of yet insufficient literature to permit assessment of projected region-specific consequences of such migration. Nevertheless, the potential for negative outcomes from migration in such complex, interactive situations is an emergent risk of climate change, with the potential to become a key risk (Box CC-KR).

19.4.2.2. Risk of Conflict and Insecurity

Violent conflict between individuals or groups arises for a variety of reasons (Section 12.5). Factors such as poverty and economic shocks that are associated with a higher risk of violent conflict are themselves sensitive to climate change and variability (*high confidence*; Sections 12.5.1, 12.5.3, 13.2). In this section, we focus on evidence for the magnitude of a climate effect on violent conflict to assess its potential to become a key risk.

The only meta-analysis of the literature (Hsiang et al., 2013), examining 60 quantitative empirical studies generally published since AR4,

implicates climatic events as a contributing factor to the onset or intensification of several types of personal violence, group conflict, and social instability in contexts around the world, at temporal scales ranging from a climatologically anomalous hour to an anomalous millennium and at spatial scales ranging from the individual level (Vrij et al., 1994; Ranson, 2012) to the communal level (Hidalgo et al., 2010; O'Loughlin et al., 2012) to the national level (Burke et al., 2009; Dell et al., 2012) to the global level (Hsiang et al., 2011). Nevertheless, some individual studies have been unable to obtain evidence that violence has a statistically significant association with climate (Buhaug, 2010; Theisen et al., 2011). In detection and attribution of their impact on human conflict, there is *low confidence* that climate change has an effect (Section 18.4.5) and *medium confidence* that climate variability has an effect.

Evidence suggests that climatic events over a large range of time and spatial scales contribute to the likelihood of violence through multiple pathways discussed in Section 12.5 (Bernauer et al., 2012; Scheffran et al., 2012; Hsiang and Burke, 2014). Results from modern contexts (1950–2010) indicate that the frequency of violence between individuals rises 2.3% and the frequency of intergroup conflict rises 13.2% for each standard deviation change toward warmer temperatures (Hsiang et al., 2013). Because annual temperatures around the world are expected to rise 2 to 4 standard deviations (as measured over 1950–2008) above temperatures in 2000 by 2050 (A1B scenario) (Hsiang et al., 2013), there is potential *ceteris paribus* for large relative changes to global patterns of personal violence, group conflict, and social instability in the future.

Social, economic, technological, and political changes that might exacerbate or mitigate this potential impact are discussed in Chapter 12. These changes may cause future populations to respond to their climate differently than modern populations; however, the influence of climate variability on rates of conflict is sufficiently large in magnitude that such advances may need to be dramatic to offset the potential influence of future climate changes.

The effect of climate change on conflict and insecurity has the potential to become a key risk because factors such as poverty and economic shocks that are associated with a higher risk of violent conflict are themselves sensitive to climate change (*medium confidence*; Sections 12.5.1, 12.5.3, 13.2), and in numerous statistical studies the influence of climate variability on human conflict is large in magnitude (*medium confidence*).

19.4.2.3. Risks Associated with Species Range Shifts

One of the primary ways species adapt to climate change is by moving to more climatically suitable areas (range shifts). These shifts will affect ecosystem functioning, potentially posing risks to ecosystem services (*medium confidence*; Millennium Ecosystem Assessment, 2005a,b; Dossena et al., 2012), including those related to climate regulation and carbon storage (Wardle et al., 2011). One example of a key impact is the warming-driven expansion and intensification of Mountain pine beetle (*Dendroctonus ponderosae*) outbreaks in North American pine forests and its current and projected impacts on carbon regulation and economies (Sections 26.4.2.1, 26.8.3). Risks also arise from projected range shifts of important resource species (e.g., marine fishes; Sections 6.5.2-3), as well as from potential introductions of diseases to people, livestock, crops, and native species (see Sections 5.4.3.5, 7.3.2.3, 22.3.5, 23.4.2, 26.6.1.6, 28.2.3). Many newly arrived species prey on, outcompete, or hybridize with existing biota (e.g., by becoming weeds or pests in agricultural systems) (Section 4.2.4.6) . The ecological implications of species reshuffling into novel, no-analog communities largely remain unknown and pose additional risks that cannot yet be assessed (Root and Schneider, 2006; Sections 6.5.3, 19.5.1, 21.4.3).

Current legal frameworks and conservation strategies face the challenge of untangling desirable species range shifts from undesirable invasions (Webber and Scott, 2012), and identifying circumstances when movement should be facilitated versus inhibited. New agreements may be needed recognizing climate change impacts on existing, new, or altered trans-boundary migration (e.g., under the Convention on the Conservation of Migratory Species of Wild Animals). As target species and ecosystems move, protected area networks may become less effective, necessitating re-evaluation and adaptation, including possible addition of sites, particularly those important as either "refugia" or migration corridors (Warren et al., 2013a; Sections 9.4.3.3, 24.4.2.5, 24.5.1). Assisted colonization—moving individuals or populations from currently occupied areas to locations with higher probability of future persistence—is arising as a potential conservation tool for species unable to track changing climates (Sections 4.4.2.4, 21.4.3). The value of these approaches, however, is contested and implementation is very limited giving *low confidence* that this would be an effective technique (Loss et al., 2011). *Ex situ* collections (Section 4.4.2.5) have often been put forward as fallback resources for conserving threatened species, yet the expense and the relatively low representation of global species and genetic diversity (Balmford et al., 2011; Conde et al., 2011) minimize the effectiveness of this technique.

19.4.3. Indirect, Trans-boundary, and Long-Distance Impacts of Mitigation Measures

Mitigation, too, can have unintended consequences beyond its boundaries, which may affect natural systems and/or human systems. If mitigation involves a form of land use change, then regional implications can ensue in the same way as they can for adaptation (see Section 14.7).

Mitigation can potentially reduce direct climate change impacts on biodiversity (Warren et al., 2013a). However, impacts on biodiversity as a result of land use change induced by biofuel production can offset benefits associated with biofuels (see Boxes 4-1, 25-10; Sections 4.2.4.1, 4.4.4, 9.3.3.4, 19.3.2.2, 22.6.3, 24.6, 27.2.2.1). Climate change mitigation through "clean energy" substitution can also have negative impacts on biodiversity. However, attention to siting and monitoring can decrease some negative ecological and socioeconomic impacts (*medium confidence*) while maximizing positive ones (Section 4.4.4). For example, the U.S. Government performed an intensive study of suitable sites for solar power on public lands in the western USA. The end result opened 285,000 acres of public land for large-scale solar deployment while blocking development on 78 million acres to protect "natural and cultural" resources (US DOE and BLM, 2012). The construction of large hydroelectric dams can affect both terrestrial and aquatic ecosystems

Frequently Asked Questions

FAQ 19.3 | How can climate change impacts on one region cause impacts on other distant areas?

People and societies are interconnected in many ways. Changes in one area can have ripple effects around the world through globally linked systems such as the economy. Globalized food trade means that changed crop productivity as a result of extreme weather events or adverse climate trends in one area can shift food prices and food availability for a given commodity worldwide. Depletion of fish stocks in one region due to ocean temperature rise can cause impacts on the price of fish everywhere. Severe weather in one area that interferes with transportation or shipping of raw or finished goods, such as refined oil, can have wider economic impacts.

In addition to triggering impacts via globally linked systems like markets, climate change can alter the movement of people, other species, and physical materials across the landscape, generating secondary impacts in places far removed from where these particular direct impacts of climate change occur. For example, climate change can create stresses in one area that prompt some human populations to migrate to adjacent or distant areas. Migration can affect many aspects of the regions people leave, as well as many aspects of their destination points, including income levels, land use, and the availability of natural resources, and the health and security of the affected populations—these effects can be positive or negative. In addition to these indirect impacts, all regions experience the direct impacts of climate change.

along river systems (World Commission on Dams, 2000; see also Sections 3.7.2.1, 4.4.4, 24.4.2.3, 24.9.1).

Mitigation strategies will have a range of effects on human systems. Reforestation that properly mimics existing forest ecosystems in structure and composition would potentially benefit human systems by stabilizing micro-climatic variation (Canadell and Raupach, 2008) and allowing benefits from the sustainable harvest of non-timber forest products for food, medicine, and other marketable commodities (Guariguata et al., 2010). However, there is a generally longer time frame and greater expense involved in recreating a diverse forest system. Afforestation creates a similar set of costs and benefits (Sections 3.7.2.1, 4.4.3, 17.2.7.1, 22.4.5.6-7; Box CC-WE). Mitigation strategies designed to reduce dependence on carbon-intensive fuels present a very different set of circumstances in relation to human systems. The development of bioresources for energy use may have significant economic and market effects potentially influencing food prices (see also Section 19.4.1). This would especially affect populations that already devote a considerable portion of their household income to food (Hymans and Shapiro, 1976).

19.5. Newly Assessed Risks

Newly assessed risks are those for which the evidence base in the scientific literature has only recently become sufficient to allow for assessment. Furthermore, these risks have at least the potential to become key based on the criteria in Section 19.2.2. Several of the emergent risks discussed in Sections 19.3 and 19.4, including those associated with human migration (Section 19.4.2.1) and mitigation measures (Section 19.4. 3), can be considered newly assessed. Others are related to diverse aspects of climate change, including the impacts of a large temperature rise, ocean acidification and other direct consequences of CO2 increases, and the potential impacts of geoengineering implemented as a climate change response strategy.

19.5.1. Risks from Large Global Temperature Rise >4°C above Preindustrial Levels

Most climate change impact studies focus on climate change scenarios corresponding to global mean temperature rises of up to 3.5°C relative to 1990 (slightly more than 4°C above preindustrial levels), with only a few examples of assessments of temperature rise significantly above that level (Parry et al., 2004; Hare, 2006; Warren et al., 2006; Easterling et al., 2007; Fischlin et al., 2007). Recently the potential for larger amounts of warming has received increasing attention and preliminary assessment of impacts above that level of warming is possible for agriculture, ecosystems, water, health, and large-scale singular events. In this section, all temperature changes are global and relative to preindustrial levels. Relevant climate scenarios include those based on RCP8.5, which in 2081–2100 is projected to result in a temperature rise of 4.3°C ± 0.7°C with temperature above 4°C *as likely as not* (WGI AR5 Section 12.4.1, Table 12.3), and some simulations using SRES A2 and A1FI, which can reach 5.9°C and 6.9°C warming, respectively, by 2100 (WGI AR4 SPM). Literature that uses these scenarios but assumes low climate sensitivity and hence less than 4°C of warming is excluded.

Relatively few studies have considered impacts on cropping systems for scenarios where global mean temperatures increase by 4°C or more (Section 7.4.1). Among these, one indicates substantial reductions in yields in sub-Saharan Africa (Thornton et al., 2011) and another indicates reversal of gains in yields and substantial reductions for Finland (Rötter et al., 2011). Other studies at or below 4 °C anticipate yield losses, particularly in tropical regions, even when taking agronomic adaptations into account (Section 7.5.1.1.1). The possibility of compensation for

these losses due to other responses of the food system to impacts on production, such as land use change and adjustment of trade patterns, cannot yet be adequately assessed for a world with GMT >4°C (Sections 19.4.1, 19.6.3.4).

Assessments of ecological impacts at and above 4°C warming imply a high risk of extensive loss of biodiversity with concomitant loss of ecosystem services (*high confidence*; Section 4.3.2.5; Table 4-3). AR4 estimated that 20 to 30% of species were likely at increasingly high risk of extinction as global mean temperatures exceed a warming of 2°C to 3°C above preindustrial levels (*medium confidence*; Fischlin et al., 2007); hence 4°C warming implies further increases to extinction risks for an even larger fraction of species. However, there is *low agreement* on the numerical assessment because as more realistic details have been considered in models, it has been shown that extinction risks may be either under- or overestimated when using the simpler models (Section 4.3.2.5), among other reasons due to the existence of microrefugias or to delay in population decline leading to extinction debts (e.g., Dullinger et al., 2012). Additional risks include biome shifts of 400 km (Gonzalez et al., 2010), the disappearance of analogs of current climates in regions of exceptional biodiversity in the Himalayas, Mesoamerica, East and South Africa, the Philippines, and Indonesia (Beaumont et al., 2011), and loss of more than half of the climatically determined geographic ranges of 57 ± 6% of plants and 34 ± 7% of animals studied (Warren et al., 2013a). Widespread coral reef mortality is expected at 4°C due to the concomitant effects of warming and a projected decline of ocean pH of 0.43 since preindustrial times (*high confidence*; WGI AR5 Figure TS.20; Section 5.4.2.4; Boxes CC-CR, CC-OA). The corresponding CO_2 concentration in such a scenario is about 900 ppm (WGI AR5 Figure 12.36) whereas the onset of large-scale dissolution of coral reefs is projected if CO_2 concentrations reach 560 ppm (Sections 5.4.2.4, 26.4.3.2).

A number of studies project increases in water stress, flood, and drought in a number of regions with >4°C warming, and decreases in others (Li et al., 2009; Arnell, 2011; Fung et al., 2011; Dankers et al., 2013; Gerten et al., 2013; Gosling and Arnell, 2013). For example, projections of the proportion of global population exposed to water stress due to climate change range from 5 to 50% (Gosling and Arnell, 2013) by 2100. The proportion of cropland exposed to drought disaster (one or more months with Palmer Drought Severity Index (PDSI) drought indicator below –3) is projected to increase from 15% today to 44 ± 6% by 2100, based on a range of projections including some that reach or exceed 4°C global warming (Li et al., 2009). Concurrently irrigation water demand in currently cultivated areas in the North Hemisphere is projected to rise by 20% in the summer by 2100 under RCP8.5 due to climate change alone (Wada et al. 2013), although this could be partly buffered by decreasing evapotranspiration due to plant physiological responses to increased atmospheric CO_2 (Konzmann et al., 2013; Box CC-VW). One study (Portmann et al., 2013) projects that, by the 2080s under the RCP8.5 scenario, 27 to 50% (mean 38%) of the global population would experience at least a 10% decrease in groundwater resources, mostly in drier areas with high population density where water stress is more likely to occur. Concurrently, 20 to 45% of the population is projected to experience at least a 10% increase in groundwater resources under RCP8.5 in the 2080s. This is projected to occur mostly in wetter areas or those with low population density where it is less probable that water stress will be an issue. Another study projects that annual runoff will fall by up to 75% across the Danube and Mississippi river basins, and by up to 90% in the Amazon; while runoff is projected to either fall (by up to 75%) or to rise (by up to 30%) in the Murray Darling, and increase by up to 150% in the Ganges basin, and up to 80% in the Nile basin (Fung et al., 2011) with 4°C warming. Both studies are based on an ensemble of climate model projections. Under RCP8.5 in 2100, nine global hydrological models driven by five global circulation models project increases in flood frequency in over half of the land surface, and decreases in roughly a third of the land surface (Dankers et al., 2013). According to one study, even if the human population remained constant in Europe, without adaptation, 3.5°C to 4.8°C global warming by the 2080s would expose an additional 250,000 to 400,00 people to river flooding, doubling economic damages since 1961 to 1990, and expose an additional 850,000 to 5,550,000 to coastal flooding (Ciscar et al., 2011), compared to 36,000 in 1995.

Under 4°C warming most of the world land area will be experiencing 4°C to 7°C higher temperatures than in the recent past, which means that important tipping points for health impacts may be exceeded in many areas of the world during this century, including coping mechanisms for daily temperature/humidity, seasonally compromising normal human activities, including growing food or working outdoors (Chapter 11 ES). Exceedance of human physiological limits is projected in some areas for a global warming of 7°C, and in most areas for global warming of 11°C to 12°C (*low confidence*; Sherwood and Huber, 2010), a temperature increase that is possible by 2300 (WGI AR5 Figure 12.5).

The risk of large-scale singular events such as ice sheet disintegration, CH_4 release from clathrates, and regime shifts in ecosystems (including Amazon dieback), is higher with increased warming (and therefore higher above 4°C than below it) although there is *low confidence* in the temperature changes at which thresholds might exist for these processes (Section 19.6.3.6; WGI AR5 Sections 12.5.5, 13.4). There are also more gradual changes that become large with global temperature rise of 4°C or more, such as decline in the Atlantic Meridional Overturning Circulation (AMOC) and release of carbon from thawed permafrost (CTP). The AMOC is considered *very likely* to weaken for such warming, with best estimates of loss over the 21st century under RCP8.5 ranging from 12 to 54% (WGI AR5 Sections 12.4.7.2, 12.5.5.2). The best estimated range for CTP by 2100 is from 50 to 250 PgC for RCP8.5 (WGI AR5 Section 6.4.3.4) although there are large uncertainties. Larger decreases in AMOC and increases in CTP are thus implied for a global warming of above 4°C. Similarly, because a nearly ice-free Arctic Ocean in September before mid-century is likely under RCP8.5, by which time projected GMT rise amounts to 2.0 ± 0.4°C above the 1986–2005 baseline (*medium confidence*; WGI AR5 Section 12.4.6.1), the likelihood is even higher for global warming of above 4°C. Regions of the boreal forest could witness widespread forest dieback (*low confidence*), putting at risk the boreal carbon sink (Section 4.3.3.1.1; WGI AR5 Section 12.5.5). Forest susceptibility to fire is projected to increase substantially in many areas for the high emissions scenario (RCP 8.5; Section 4.3.3.1; Figure 4-6) and hence larger changes are implied for global warming above 4°C.

Based on the assessment in this section, we conclude that climate change impacts at 4°C and above would be of greater magnitude and

more widespread than at lower levels of global temperature rise (*medium evidence*, *high agreement*; *high confidence*), extending to higher temperature levels previous findings that risks increase with increasing global average temperature (WGII AR4 SPM.2; National Research Council, 2011). Few studies yet consider the interactions between these effects, which could create significant additional risks (Warren et al., 2011; Sections 19.3-4).

19.5.2. Risks from Ocean Acidification

Ocean acidification is defined as "a reduction in pH of the ocean over an extended period, typically decades or longer, caused primarily by the uptake of carbon dioxide (CO_2) from the atmosphere" (WGI AR5 Section 3.3.2, Box 3.2; Box CC-OA; see also Glossary). Acidification is a physical and biogeochemical impact resulting from CO_2 emissions that poses risks to marine ecosystems and the societies that depend on them. Research on impacts on organisms, ecological responses, and consequences for ecosystem services is relatively new; the potential for associated risks to become key is magnified by the fact that acidification is a global phenomenon and, without a decrease in atmospheric CO_2 concentration, it is irreversible on century time scales.

It is *virtually certain* that ocean acidification is occurring now (WGI AR5 Section 3.9) and will continue to increase in magnitude as long as the atmospheric CO_2 concentration increases (National Research Council, 2010). Risks to society and ecosystems result from a chain of consequences beginning with direct effects on biogeochemical processes and organisms and extending to indirect effects on ecosystems, ecosystem services, and society (Figure 19-3). The degree of confidence in assessing risks decreases along this chain owing to the complexity of interactions across these scales and the relatively small number of studies available for quantitative risk assessment.

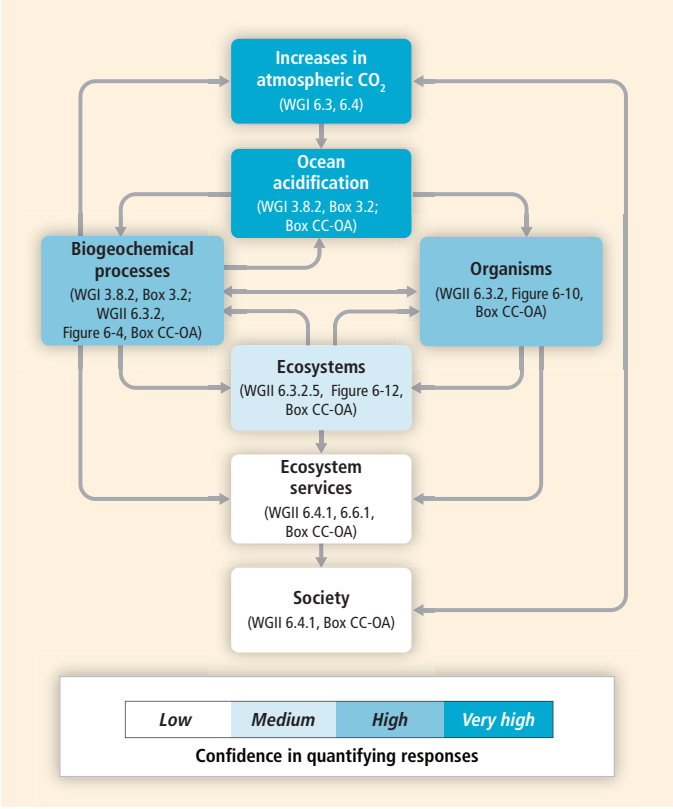


Figure 19-3 | The pathways by which ocean acidification affects marine processes, organisms, ecosystems, and society. The confidence in quantifying the impacts decreases along the pathway.

Most studies have focused on the direct effects of ocean acidification on marine organisms and biogeochemical processes. The overall effects on organisms can be assessed with *medium confidence* (Section 6.3.2; Box CC-OA), but the effects vary widely across processes (e.g., photosynthesis, growth, calcification; Section 6.3.2) and across organisms and their life stages (Section 6.3.2; Box CC-OA).

Far fewer studies have assessed the impacts on ecosystems (Section 6.3.2.5) and ecosystem services (Section 6.4.1), and most of these studies have focused on the economic impacts on fisheries (Section 6.4.1.1). For example, changes in overall availability and nutritional value of desired mollusk species could affect economies (Narita et al., 2012) and food availability (Section 6.4.1.1). In Table 19-3, we assess the risks to ecosystem services through the impact of acidification on two key marine processes, calcification in warmwater corals and nitrogen fixation, using the criteria for key risks (Section 19.2.2.2).

Based on Table 19-3, the response of coral calcification to ocean acidification and the resulting consequences for coral reefs constitute a key risk to important ecosystem services (*high confidence*). The effect of ocean acidification on marine N_2-fixation could potentially become a key risk, given that it could have potentially large consequences for marine ecosystems, but currently there is *limited evidence* on the likelihood of this risk materializing.

19.5.3. Risks from Carbon Dioxide Health Effects

There is increasing evidence that the impacts of elevated atmospheric CO_2 on plant species will affect health via two distinct pathways: the increased production and allergenicity of pollen and allergenic compounds, and the nutritional quality of key food crops. The evidence for these impacts on plant species is increasingly *robust* and recent evidence in the public health literature points to a *medium* to *high confidence* in the potential for these risks to be sufficiently widespread in geographical scope and large in *magnitude* of their impact on human health to be considered key risks.

Climate change is expected to alter the spatial and temporal distribution of several key allergen-producing plant species (Shea et al., 2008), and increased atmospheric CO_2 concentration, independent of climate effects, has been shown to stimulate pollen production (Rasmussen, 2002; Clot, 2003; Galán et al., 2005; Garcia-Mozo et al., 2006; Ladeau and Clark, 2006; Damialis et al., 2007; Frei and Gassner, 2008). A series of studies (Ziska and Caulfield, 2000; Ziska et al., 2003; Ziska and Beggs, 2012) found an association of elevated CO_2 concentrations and temperature with faster growing and earlier flowering ragweed species (*Ambrosia artemisiifolia*) along with greater production of ragweed pollen (Wayne et al., 2002; Singer et al., 2005; Rogers et al., 2006), leading, in some areas, to a measurable increase in hospital visits for allergic rhinitis

Table 19-3 | An assessment of the risks to ecosystem services posed by the impacts of ocean acidification on warm-water coral calcification and nitrogen fixation, based on the four criteria for key risks (Section 19.2.2.2).

Criterion for key risk	Coral calcification	Nitrogen fixation
1. Magnitude of consequences for ecosystem services	Ecosystem services include supporting habitats, provisioning of fish, regulating shoreline erosion, and tourism. Potential magnitude of consequences is medium to high (Box CC-CR).	Ecosystem services include nitrogen cycling, which supports ecosystem structure and food chains (Hutchins et al., 2009). Potential magnitude of consequences has not been investigated.
2. Likelihood that risks will materialize and their timing	A reduction in coral calcification rate and an increase in reef dissolution rates are *very likely* (Section 6.1.2), so that reefs will progressively shift toward net dissolution (*medium confidence*; Section 5.4.2.4; Boxes CC-CR and CC-OA).	Both increases and decreases in nitrogen fixation have been observed in various N_2-fixing organisms (Section 6.3.2.2) but there is *limited* in situ *evidence* and *medium agreement* on how N_2-fixation rates will change in response to ocean acidification.
3. Irreversibility and persistence of ocean acidification impacts	Decreases in ocean pH will persist as long as atmospheric CO_2 levels remain elevated (WGI AR5 Section 3.8.2). Reductions in coral calcification will persist unless corals can physiologically adapt to maintain calcification rates. Reversibility of impacts on ecosystem services of coral reefs is unknown and depends on ecological factors such as hysteresis.	Decreases in ocean pH will persist as long as atmospheric CO_2 levels remain elevated (WGI AR5 Section 3.8.2). Reversibility and persistence of impacts on nitrogen fixation are unknown.
4. Limited ability to reduce the magnitude and frequency or nature of ocean acidification impacts	Reduction of ocean acidification will require global reductions in atmospheric CO_2. Feasibility of mitigating ocean acidification at the local scale is unknown.	Reduction of ocean acidification will require global reductions in atmospheric CO_2.

(Breton et al., 2006). Experimental studies have shown that poison ivy, another common allergenic species, responds to atmospheric CO_2 enrichment through increased photosynthesis, water use efficiency, growth, and biomass. This stimulation, exceeding that of most other woody species, also produces a more potent form of the primary allergenic compound, urushiol (Mohan et al., 2006).

While climate change and variability are expected to affect crop production (see Chapter 7), emerging evidence suggests an additional stressor on the food system: the impact of elevated levels of CO_2 on the nutritional quality of important foods. A prominent example of the effect of elevated atmospheric CO_2 is the decrease in the nitrogen concentration in vegetative plant parts as well as in seeds and grains and, related to this, the decrease in the protein concentrations (Cotrufo et al., 1998; Taub et al., 2008; Wieser et al., 2008). Experimental studies of increasing CO_2 to 550 ppm demonstrated effects on crude protein, starch, total and soluble beta-amylase, and single kernel hardiness, leading to a reduction in crude protein by 4 to 13% in wheat and 11 to 13% in barley (Erbs et al., 2010). Other CO_2 enrichment studies have shown changes in the composition of other macro- and micronutrients (calcium, potassium, magnesium, iron, and zinc) and in concentrations of other nutritionally important components such as vitamins and sugars (Idso and Idso, 2001). Declining nutritional quality of important global crops is a potential risk that would broadly affect rates of protein-energy and micronutrient malnutrition in vulnerable populations. While there is *medium confidence* that this risk has the potential to become key when judged by its *magnitude* and other criteria (Sections 19.2.2.1-2) there is currently insufficient information to assess under what ambient CO_2 concentrations this would occur.

19.5.4. Risks from Geoengineering (Solar Radiation Management)

Geoengineering refers to a set of proposed methods and technologies that aim to alter the climate system at a large scale to alleviate the impacts of climate change (see Glossary; IPCC, 2012b; WGI AR5 Sections 6.5, 7.7; WGIII AR5 Chapter 6). The main intended benefit of geoengineering would be the reduction of climate change that would otherwise occur, and the associated reduction in impacts (Shepherd et al., 2009). Here we focus on risks, consistent with the goal of this chapter. Although geoengineering is not a new idea (e.g., Rusin and Flit, 1960; Budyko and Miller, 1974; Enarson and Morrow, 1998; and a long history of geoengineering proposals as detailed by Fleming, 2010), it has received increasing attention in the recent scientific literature.

Geoengineering has come to refer to both carbon dioxide removal (CDR; discussed in detail in WGI AR5 Section 6.5, FAQ 7.3) and Solar Radiation Management (SRM; Izrael et al., 2009; Lenton and Vaughan, 2009; Shepherd et al., 2009; discussed in detail in WGI AR5 Section 7.7, FAQ 7.3). These distinct approaches to climate control raise very different scientific (e.g., Shepherd et al., 2009), ethical (Morrow et al., 2009; Preston, 2013), and governance (Lloyd and Oppenheimer, 2014) issues. Many approaches to CDR are considered to more closely resemble mitigation rather than other geoengineering methods (IPCC, 2012b). In addition, CDR is thought to produce fewer risks than SRM if the CO_2 can be stored safely (Shepherd et al., 2009) and unintended consequences for land use, the food system, and biodiversity can be avoided (Section 19.4.3). For these reasons, in addition to the more substantial recent literature on SRM's potential impacts, we address only SRM in this section. SRM is a potential key risk because it is associated with impacts to society and ecosystems that could be large in magnitude and widespread. Current knowledge on SRM is limited and our confidence in the conclusions in this section is *low*.

Studies of impacts on society and ecosystems have been based on two of the various SRM schemes that have been suggested: stratospheric aerosols and marine cloud brightening. These approaches in theory could produce large-scale cooling (Salter et al., 2008; Lenton and Vaughan, 2009), although it is not clear that it is even possible to produce a stratospheric sulfate aerosol layer sufficiently optically thick to be effective (Heckendorn et al., 2009; English et al., 2012). Observations of volcanic eruptions, frequently used as an analog for SRM (Robock et al., 2013), indicate that while stratospheric aerosols can reduce the global average surface air temperature, they can also produce regional drought (e.g., Oman et al., 2005, 2006; Trenberth and Dai, 2007), cause ozone depletion (Solomon, 1999), and reduce electricity generation from solar generators that use focused direct sunlight (Murphy, 2009). Climate modeling studies show that the risk of ozone depletion depends in detail on how much and when stratospheric aerosols would be

released in the stratosphere (Tilmes et al., 2008) and find that global stratospheric SRM would produce uneven surface temperature responses and reduced precipitation (Schmidt et al., 2012; Kravitz et al., 2013), weaken the global hydrological cycle (Bala et al., 2008), and reduce summer monsoon rainfall relative to current climate in Asia and Africa (Robock et al., 2008). Hemispheric geoengineering would have even larger effects (Haywood et al., 2013).

The net effect on crop productivity would depend on the specific scenario and region (Pongratz et al., 2012). Use of SRM also poses a risk of rapid climate change if it fails or is halted suddenly (WGI AR5 Section 7.7; Jones et al., 2013), which would have large negative impacts on ecosystems (*high confidence*; Russell et al., 2012) and could offset the benefits of SRM (Goes et al., 2011). There is also a risk of "moral hazard"; if society thinks geoengineering will solve the global warming problem, there may be less attention given to mitigation (e.g., Lin, 2013). In addition, without global agreements on how and how much geoengineering to use, SRM presents a risk for international conflict (Brzoska et al., 2012). Because the direct costs of stratospheric SRM have been estimated to be in the tens of billions of U.S. dollars per year (Robock et al., 2009; McClellan et al., 2012), it could be undertaken by non-state actors or by small states acting on their own (Lloyd and Oppenheimer, 2014), potentially contributing to global or regional conflict (Robock, 2008a,b). Based on magnitude of consequences and exposure of societies with limited ability to cope, geoengineering poses a potential key risk.

19.6. Key Vulnerabilities, Key Risks, and Reasons for Concern

In this section, we present key vulnerabilities, key risks, and emergent risks that have been identified by many of the chapters of this report based on the material assessed by each in light of criteria discussed in Sections 19.2.2 and 19.2.3. We then discuss dynamic characteristics of exposure, vulnerability, and risk, features that are influenced by development pathways in the past, present, and future. Illustrative examples of climate-related hazards, key vulnerabilities, key risks, and emergent risks in Table 19-4 are representative, having been selected from a larger number provided by the chapters of this report. The table demonstrates how these four categories are related, as well as how they differ, and how they interact with non-climate stressors. The table also provides information on how key risks actually develop due to changing climatic hazards and vulnerabilities. This knowledge is an important prerequisite for effective adaptation and risk reduction strategies that must address climate-related hazards, non-climatic stressors, and various vulnerabilities that often interact in complex ways and change over time.

19.6.1. Key Vulnerabilities

Several of the risks discussed in this and other chapters and noted in Table 19-4 arise because vulnerable people must cope and adapt not only to changing climate conditions, but also to multiple, interacting stressors simultaneously (see Sections 19.3-4), which means that effective adaptation strategies would address these complexities and relationships.

19.6.1.1. Dynamics of Exposure and Vulnerability

This subsection deals with the meaning and the importance of dynamics of exposure and vulnerability, while Section 19.6.1.3 assesses recent literature regarding observed trends of vulnerability mostly at a global or regional scale. The literature provides increasing evidence that structures and processes that determine vulnerability are dynamic and spatially variable (IPCC, 2012a; Section 19.6.1.3). SREX states with *high confidence* that vulnerability and exposure of communities or social-ecological systems to climatic hazards related to extreme events are dynamic, thus varying across temporal and spatial scales due to influences of and changes in social, economic, demographic, cultural, environmental, and governance factors (IPCC, 2012c, SPM.B).

Examples of such dynamics in exposure and vulnerability encompass, for example, population dynamics, such as population growth or changes in poverty (Table 19-4; Birkmann et al., 2013b) and increasing exposure of people and settlements in low-lying coastal areas or flood plains in Asia (see Nicholls and Small, 2002; Fuchs et al., 2011; IPCC, 2012a; Peduzzi et al., 2012). Also, demographic changes, such as aging of societies, have a significant influence on people's vulnerability to heat stress (see Stafoggia et al., 2006; Gosling et al., 2009). Changes in poverty or socioeconomic status, ethnic compositions, as well as age structures had a significant influence on the outcome of past crises and in addition were modified and reinforced through disasters triggered by climate- and weather-related hazards. For the USA, for example, Cutter and Finch (2008) found that social vulnerability to natural hazards increased over time in some areas owing to changes in socioeconomic status, ethnic composition, age, and density of population. Changes in the strength of social networks (e.g., resulting in social isolation of elderly) and physical abilities to cope with such extreme events modify vulnerability (see, e.g., Khunwishit and Arlikatti, 2012).

In some cases human vulnerability might also change in different phases of crises and disasters. Hence, the factors that might determine vulnerability before a crisis or disaster (drought crises, flood disaster) might differ from those that determine vulnerability thereafter (post-disaster and recovery phases). Disaster response and reconstruction processes and policies can modify exposure and vulnerability, for example, of coastal communities (Birkmann and Fernando, 2008; Birkmann, 2011). A comprehensive assessment of vulnerability would account for these dynamics by evaluating long-distance impacts (e.g., resulting from migration or global influence of regional crop production failures following floods) and multiple stressors (e.g., recovery policies after disasters) that often influence dynamics and generate complex crises and even emergent risks. Furthermore, SREX also underscores that the increased intensity, frequency, and duration of some extreme events as climate continues to change might make adaptation based only on recent experience or the extrapolation of historical trends largely ineffective (Lavell et al., 2012, pp. 44–47); hence understanding the dynamics of vulnerability and its different facets is crucial.

19.6.1.2. Differential Vulnerability and Exposure

Wealth, education, ethnicity, religion, gender, age, class/caste, disability, and health status exemplify and contribute to the differential exposure

and vulnerability of individuals or societies to climate and non-climate-related hazards (see IPCC, 2012a). Differential vulnerability is, for example, revealed by the fact that people and communities that are similarly exposed encounter different levels of harm, damage, and loss as well as success of recovery (see Birkmann, 2013). The uneven effects and uneven suffering of different population groups and particularly marginalized groups is well documented in various studies (Bohle et al., 1994; Kasperson and Kasperson, 2001; Birkmann, 2006a; Thomalla et al., 2006; Sietz et al., 2011, 2012). Factors that determine and influence these differential vulnerabilities to climate-related hazards include, for example, ethnicity (Fothergill et al., 1999; Elliott and Pais, 2006; Cutter and Finch, 2008), socioeconomic class, gender, and age (O'Keefe et al., 1976; Sen, 1981; Peacock, 1997; Jabry, 2003; Wisner, 2006; Bartlett, 2008; Ray-Bennett, 2009), as well as migration experience (Cutter and Finch, 2008) and homelessness (Wisner, 1998; IPCC, 2012a). Differential vulnerabilities of specific populations can often be discerned at a particular scale using quantitative or qualitative assessment methodologies (Cardona, 2006, 2008; Birkmann et al., 2013b). Various population groups are differentially exposed to and affected by hazards linked to climate change in terms of both gradual changes in mean properties and extreme events. For example, in urban areas, marginalized groups (particularly as a result of gender or wealth status or ethnicity) often settle along rivers or canals, where they are highly exposed to flood hazards or potential sea level rise (see Table 19-4; e.g., Neal and Phillips, 1990; Enarson and Morrow, 1998; Neumayer and Plümper, 2007; Sietz et al., 2012). Studies emphasize that vulnerability in terms of gender is not determined through biology, but in most cases by social structures, institutions, and rule systems; hence women and girls are often (not always) more vulnerable because they are marginalized from decision making or experience discrimination in development and reconstruction efforts (Fordham, 1998; Houghton, 2009; Sultana, 2010; IPCC, 2012a).

19.6.1.3. Trends in Exposure and Vulnerability

Vulnerability and exposure of societies and social-ecological systems to hazards linked to climate change are dynamic and depend on economic, social, demographic, cultural, institutional, and governance factors (see IPCC, 2012c, p. 7). The literature shows that there is a *high confidence* that rapid and unsustainable urban development, international financial pressures, increases in socioeconomic inequalities, failures in governance (e.g., corruption), and environmental degradation are key trends that modify vulnerability of societies, communities, and social-ecological systems (Maskrey, 1993a,b, 1994, 1998; Mansilla, 1996; Cannon, 2006; Birkmann, 2013; de Sherbinin, 2014) at different scales. Consequently, many of the factors that reveal and determine differential vulnerability change over time in terms of their spatial distribution. These dynamics unfold in different places differently and therefore local or regional specific strategies are needed that strengthen resilience (Garschagen and Kraas, 2011; Holdschlag and Ratter, 2013) and reduce exposure and vulnerability. For example, countries characterized by rapid urbanization coupled with low economic performance and high social development barriers face among the highest levels of climate change vulnerability. However, urbanization in some areas can yield conditions conducive to building up coping and adaptation capacities particularly when urban socioeconomic development and risk management is properly implemented (see Garschagen and Romero-Lankao, 2013). The following subsections outline observed trends in vulnerability according to different thematic dimensions (e.g., socioeconomic, environmental, institutional), within the constraint that relevant socioeconomic data are limited.

19.6.1.3.1. Trends in socioeconomic vulnerability

Multi-dimensional poverty is an important factor determining vulnerability of societies to climate change and extreme events (Section 13.1.4). For example, risk due to droughts, particularly in sub-Saharan Africa, is intimately linked to poverty and rural vulnerability (*high confidence*; see World Bank, 2010; Birkmann et al., 2011b; UNISDR, 2011, p. 62; Welle et al., 2012). In interpreting the following estimates, it should be borne in mind that diverse concepts of poverty lead to different estimates but that for some regions, e.g., sub-Saharan Africa, the trends are *robust*. Recent evaluation of conditions in 119 countries found that at the international level there had been a clear decrease in global poverty over the previous 6 years (Chandy and Gertz, 2011). The number of poor people globally fell, from more than 1.3 billion in 2005 to fewer than 900 million in 2010. This trend is expected to continue (e.g., Hughes et al., 2009; Chandy and Gertz 2011). However, regional trends vary, as do differences between emerging and least developed economies. As a result, there is a growing climate-related risk in some regions associated with chronic poverty. For example, in 2010, approximately 48.5% of the population of the highly drought exposed region sub-Saharan Africa still lives in poverty (poverty headcount ration at $1.25 per day; see World Bank, 2012) and this area already has been defined as a global risk hotspot (see Birkmann et al., 2011b; Welle et al., 2012). However, various national-level poverty statistics provide little information about the actual distribution of poverty, for example, between rural vs. urban areas. Income distribution trends show significant increases in inequality in some countries in Africa, and particularly in Asia, such as in China, India, Indonesia, and Bangladesh (World Bank, 2012). In Asia and Southeast Asia this trend overlaps with areas of compound climate risk (Section 19.3.2.4) in terms of people currently exposed to floods and tropical cyclones as well as sea level rise (Förster et al., 2011; IPCC, 2012a; Peduzzi et al., 2012). Assessing vulnerability (and risk) in these countries requires in-depth analysis of trends and distribution patterns of poverty, income disparities, and exposure of people to changing climatic hazards.

New socioeconomic vulnerabilities are emerging in some countries, for example, in developed countries, where the impoverishment of some population groups is observed. For example, research underscores that old age increases the risk of poverty in Greece, as the majority of people working as farmers or in the private sector receive small pensions that are below the poverty line (Karamessini, 2010, p. 279). These factors might interact with limited physical means of elderly to cope with climatic hazards, such as heat waves, and hence increase vulnerability.

Health status of individuals and population groups affects vulnerability to climate change by limiting capacities to cope and adapt to climate hazards (see Chapter 11). Although at a global scale the percentage of people undernourished is decreasing (FAO, 2012) and this trend is expected to continue (Hughes et al., 2009), the regional and national differences are significant: during 2010–2012, 870 million people

remained chronically undernourished (FAO, 2012). Particularly in certain regions highly exposed to current and projected climate-related hazards, the number of people undernourished has increased. In sub-Saharan Africa, where exposure to drought is episodically high, the number of undernourished increased by 64 million or about 38% during 2010–2012 compared to 1990–1992 (Hughes et al., 2009; FAO, 2012, p. 10). Moreover, at many locations, climate change is expected to reduce the access to and the quality of natural resources that are important to sustain rural and urban livelihoods as well as the capacities of states to provide help to sustain livelihoods (Barnett and Adger, 2007; see also Section 19.3.2.1). These multi-risk contexts require new approaches for climate change adaptation.

While these trends mainly point to particularly large exposure and vulnerability in developing countries, studies regarding extreme heat vulnerability, for example, underscore that developed countries face increasing challenges to adaptation as well. Heat waves are projected to increase in duration, intensity, and extent (WGI AR5 Section 11.3.2). Advanced age represents one of the most significant risk factors for heat-related death (Bouchama and Knochel, 2002) because, in addition to limited thermoregulatory and physiologic heat-adaptation capacities, elderly have often reduced social contacts, and a higher prevalence of chronic illness and poor health (Section 11.3.3; Khosla and Guntupalli, 1999; Klinenberg, 2002; O'Neill, 2003). The trend toward an aging society, for example in Japan or Germany, therefore increases the vulnerability of these societies to extreme heat stress.

19.6.1.3.2. Trends in environmental vulnerability

Societies depend on ecosystem services for their survival; however, these ecosystem services and functions (see, e.g., Millenium Ecosystem Assessment, 2005a,b) are vulnerable to climate change (see Cardona et al., 2012, pp. 76–77; Table 19-4; Section 19.3.2.1). Various societies and communities that rely heavily on the quality of ecosystem services, such as rural populations dependent on rainfed agriculture where drying is projected (see also Table 19-4), will experience increased risk from climate change owing to its negative influence on ecosystem services (*high confidence*; see Sections 4.3.4, 6.4.1).

Although no global overview is available, recent reports (UNDP, 2007; IPCC, 2012a) underscore that a number of current environmental trends threaten human well-being and thus increase human vulnerability (UNEP, 2007). Many communities that have suffered large losses due to extreme weather events—for example, coastal flooding—also experienced earlier degradation of ecosystems providing protective services. Recent global studies and local studies, such as for the U.S. East Coast, underscore that intact ecosystems, such as marshes, can have an important protective role against coastal hazards for example, by wave attenuation (Shepard et al., 2011; Beck et al., 2013). Hence, coastal degradation, such as destruction of coral reefs in Asia, is increasing the exposure of communities to such hazards (Welle et al., 2012). Moreover, the extinctions of species and the loss of biodiversity pose a threat of diminution of genetic pools that otherwise buffer the adaptive capacities of social-ecological systems dependent on these services in the medium and long run (e.g., in terms of medicine and agricultural production).

19.6.1.3.3. Trends in institutional vulnerability

Institutional vulnerability refers, among other issues, to the role of governance. Governance is increasingly recognized as a key factor that influences vulnerability and adaptive capacity of societies and communities exposed to extreme events and gradual climate change (Kahn, 2005; Nordås and Gleditsch, 2007; Welle et al., 2012). People in countries or places that are facing severe failure of governance, such as violent conflicts (e.g., Somalia, Afghanistan) are particularly vulnerable to extreme events and climate change, as they are already exposed to complex emergency situations and hence have limited capacities to cope or undertake effective risk management (see Ahrens and Rudolph, 2006; Menkhaus, 2010). Countries classified as failed states are often not able to guarantee their citizens basic standards of human security and consequently do not provide adequate or any support in crises or disaster situations for vulnerable people. The Failed State Index (Foreign Policy Group, 2012; Fund for Peace, 2012) as well as the Corruption Perception Index (Transparency International, 2012) are used to characterize institutional vulnerability and governance failure. Trends in the Failed State Index from 2006 to 2011 show that countries with severe problems in the functioning of the state cannot easily shift or change their situation (persistence of institutional vulnerability). Studies at the global level also confirm that countries classified as failed states and affected, for example, by violence are not able to effectively reduce poverty compared to countries without violence (see World Bank, 2011). Countries characterized in the literature as substantially failing in governance or in some particular aspects of governance during some period, such as Somalia and Ethiopia, Afghanistan, or Haiti have shown in the past severe difficulties in dealing with extreme events or supporting people that have to cope and adapt to severe droughts, storms, or floods (see, e.g., Lautze et al., 2004; Ahrens and Rudolph, 2006; Menkhaus, 2010, pp. 320-341; Heine and Thompson, 2011; Khazai et al., 2011, pp. 30-31). In addition, it is probable that climate change will undermine the capacity of some states to provide the services and support that help people to sustain their livelihoods in a changing climate (Barnett and Adger, 2007). Governance failure and violence as characteristics of institutional vulnerability have significant influence on socioeconomic and therefore climatic vulnerability. Furthermore, corruption has been identified as an important factor that hinders effective adaptation policies and crisis response strategies (Birkmann et al., 2011b; Welle et al., 2012). At the local level, various aspects of governance in developing and developed countries, particularly institutional capacities and self-organization, as well as political and cultural factors, are critical for social learning, innovations, and actions that can improve risk management and adaptation to climate related risks and for empowering highly vulnerable groups (IPCC, 2012a). Overall, unless governance improves in countries with severe governance failure, risk will increase and human security will be further undermined there as a result of climate change and increased human vulnerability (*high confidence*; Lautze et al., 2004; Ahrens and Rudolph, 2006; Barnett and Adger, 2007; Menkhaus, 2010).

19.6.1.4. Risk Perception

Risk perceptions influence the behavior of people in terms of risk preparedness and adaptation to climate change (Burton et al., 1993; van Sluis and van Aalst, 2006; IPCC, 2012a). Factors that shape risk

perceptions and therewith also influence actual and potential responses (and thus exposure, vulnerability, and risk) include (1) interpretations of the threat, including the understanding and knowledge of the root cause of the problem; (2) exposure and personal experience with the events and respective negative consequences, particularly recently (i.e., availability); (3) priorities of individuals; (4) environmental values and value systems in general (see, e.g., O'Connor et al., 1999; Grothmann and Patt, 2005; Weber, 2006; Kuruppu and Liverman, 2011). Furthermore, the perceptions of risk and reactions to such risk and actual events are also shaped by motivational processes (Weber, 2010). In this context people will often ignore predictions of climate-related hazards if those predictions fail to elicit emotional reactions. In contrast, if the event or forecast of such an event elicits strong emotional feelings of fear, people may overreact and panic (see Slovic et al., 1982; Slovic, 1993, 2010; Weber, 2006). Public perceptions of risks are not determined solely by the "objective" information, but rather are the product of the interaction of such information with psychological, social, institutional, and cultural processes and norms that are partly subjective, as demonstrated in various crises in the context of extreme events (Kasperson et al., 1988; Funabashi and Kitazawa, 2012). Risk perceptions particularly influence and increase vulnerability in terms of false perceptions of security (Cardona et al., 2012, p. 70). Finally, it is important to acknowledge that everyday concerns and satisfaction of basic needs may prove more pressing than attention and effort toward actions to address longer-term risk factors, e.g., climate change (Maskrey, 1989, 2011; Wisner et al., 2004). Rather, peoples' worldviews and political ideologies guide attention toward events that threaten their preferred social order (Douglas and Wildavsky, 1982; Kahan, 2010).

19.6.2. Key Risks

19.6.2.1. Assessing Key Risks

Key risks arise from the interaction of climate-related hazards and key vulnerabilities of societies, communities, or systems exposed (see Figure 19-1). Various chapters in this report have assessed key risks from their particular perspectives. We asked each chapter writing team to provide Chapter 19 authors with the key risks of highest concern to their chapter based on the criteria for defining key risks and key vulnerabilities as outlined in Section 19.2.2. A complete presentation of the key risks provided is found in Box CC-KR (allowing for some condensation by authors of Chapter 19 to avoid repetition).

The key risks provided by the chapters represent the issues most pressing to each set of experts. The list is neither unique nor exhaustive: other authors might express other preferences; however, this compilation provides important insights about key risks and their determinants—hazard, exposure, and vulnerability.

Chapter 19 authors further consolidated these key risks in Table 19-4 in order to produce the following list which, in their judgment (*high confidence*), is representative of the range of key risks forwarded. Roman numerals preceding each key risk correspond with entries in Table 19-4. Each key risk is followed with a notation in brackets indicating the Reason(s) for Concern (RFCs; see Section 19.6.3) with which it is aligned. In addition, a representative set of lines of sight is provided from across the chapters. Examples of these risks are also displayed geographically in Figure 19-2:

i) *Risk of death, injury, ill-health, or disrupted livelihoods in low-lying coastal zones and small island developing states and other small islands, due to storm surges, coastal flooding, and sea level rise*. These risks further increase in regions where the capacity to adapt long-lived coastal infrastructure (e.g. electricity, water and sanitation infrastructure) to local sea level rise beyond 1 m is limited. Urban populations with substandard housing and inadequate insurance, as well as marginalized rural populations with multidimensional poverty and limited alternative livelihoods are particularly vulnerable to these hazards. Inadequate local governmental attention to disaster risk reduction and adaptation can further increase the vulnerability of people and also the risk of adverse consequences (WGI AR5 Sections 3.7, 13.5; WGI AR5 Table 13.5; Sections 5.4.3, 8.1.4, 8.2.3-4, 13.1.4, 13.2.2, 24.4-5, 26.7-8, 29.3.1, 30.3.1; Boxes 25-1, 25-7). [RFC 1, 2, 3, 4, and 5]

ii) *Risk of severe ill-health and disrupted livelihoods for large urban populations due to inland flooding in some regions*. Particularly vulnerable are marginalized and poverty-stricken residents in low-income informal settlements as well as children, the elderly, and the disabled that have limited means to cope and adapt. Risks are increasing due to rapid and unsustainable urbanization especially in areas where risk governance capacities are constrained or limited attention is given to risk reduction and adaptation measures. Also, overwhelmed, aging, poorly maintained, and inadequate infrastructure (e.g., drainage infrastructure, electricity, water supply, etc.) can further increase the risk of severe harm and threats to human security in the case of inland flooding (WGI AR5 FAQ 12.2; Sections 3.2.7, 3.4.8, 8.2.3-4, 13.2.1, 25.10, 26.3, 26.7-8, 27.3.5; Box 25-8). [RFC 2 and 3]

iii) *Systemic risks due to extreme weather events leading to breakdown of infrastructure networks and critical services such as electricity, water supply, and health and emergency services*. Interdependency of critical infrastructure increases the risk of systemic breakdowns of vital services, for example, the risk of failure in systems dependent on electric power (such as drainage systems reliant on electric pumps) during extreme events. Health and emergency services rely on critical infrastructure (e.g., telecommunication) that can be disrupted during such power failures. For example, Hurricane Katrina left 1220 electricity-dependent drinking water systems in Louisiana, Mississippi, and Alabama inoperable for several weeks (Copeland, 2005). Overly hazard-specific management planning and infrastructure design and/or low forecasting capabilities exacerbate such risks (WGI AR5 Section 11.3.2; Sections 8.1.4, 8.2.4, 10.2-3, 12.6, 23.9, 25.10, 26.7-8). [RFC 2, 3, and 4]

iv) *Risk of mortality and morbidity during periods of extreme heat, particularly for vulnerable urban populations and those working outdoors in urban or rural areas*. Increasing frequency and intensity of extreme heat (including exposure to the urban heat island effect and air pollution) interacts with an inability of some local organizations that provide health, emergency, and social services to adapt to new risk levels for vulnerable groups. In addition, the impact of heat stress on aging populations, such as during the heat wave disaster in 2003 in Europe, shows how changing climatic conditions interact with trends in population structure, health conditions, and social isolation (characteristics of vulnerability) to create key risks (WGI AR5 Section 11.3.2; Sections 8.2.3, 11.3,

11.4.1, 13.2, 23.5.1, 24.4.6, 25.8.1, 26.6, 26.8; Box CC-HS). [RFC 2 and 3]

v) *Risk of food insecurity and the breakdown of food systems linked to warming, drought, flooding, and precipitation variability and extremes, particularly for poorer populations in urban and rural settings*. This risk is a particular concern for farmers who are net food buyers and people in low-income, agriculturally dependent economies that are net food importers). Climatic hazards and the vulnerability of people (see above) may exacerbate malnutrition, giving rise to a larger burden of disease in these groups, especially among elderly and female-headed households having limited ability to cope. The reversal of progress in reducing malnutrition is a potential outcome (WGI AR5 Section 11.3.2; Sections 7.3-5, 11.3, 11.6.1, 13.2.1-2, 19.3.2, 19.4.1, 22.3.4, 24.4, 26.8, 27.3.4). [RFC 2, 3 and 4]

vi) *Risk of loss of rural livelihoods and income due to insufficient access to drinking and irrigation water and reduced agricultural productivity, particularly for farmers and pastoralists with minimal capital in semi-arid regions*. Interaction of warming and drought with lack of alternative sources of income, and the presence of regional and national conditions that lead to a breakdown of food

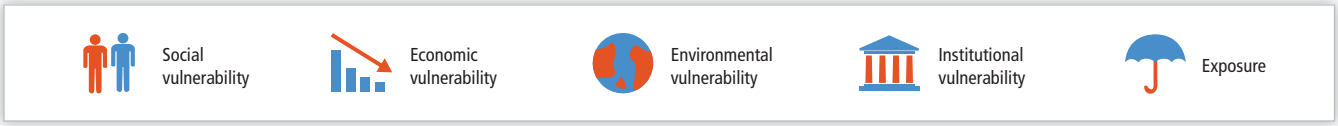
Table 19-4 | A selection of the hazards, key vulnerabilities, key risks, and emergent risks identified in various chapters in this report (Chapters 4, 6, 7, 8, 9, 11, 13, 19, 22, 23, 24, 25, 26, 27, 28, 29, and 30). Key risks are determined by hazards interacting with vulnerability and exposure of human systems and of ecosystems or species. The table underscores the complexity of risks determined by various climate-related hazards, non-climatic stressors, and multifaceted vulnerabilities. The examples show that underlying phenomena, such as poverty or insecure land tenure arrangements, unsustainable and rapid urbanization, other demographic changes, failure in governance and inadequate governmental attention to risk reduction, and tolerance limits of species and ecosystems that often provide important services to vulnerable communities, generate the context in which climatic change–related harm and loss can occur. The table illustrates that current global megatrends (e.g., urbanization and other demographic changes) in combination and in specific development contexts (e.g., in low-lying coastal zones) can generate new systemic risks in their interaction with climate hazards that exceed existing adaptation and risk management capacities, particularly in highly vulnerable regions, such as dense urban areas of low-lying deltas. Roman numerals correspond with key risks listed in Section 19.6.2.1. A representative set of lines of sight is provided from across WGI AR5 and WGII AR5. See Section 19.6.2.1 for a full description of the methods used to select these entries.

No.	Hazard	Key vulnerabilities		Key risks	Emergent risks
i	Sea level rise, coastal flooding including storm surges (WGI AR5 Sections 3.7 and 13.5; WGI AR5 Table 13.5; Sections 5.4.3, 8.1.4, 8.2.3, 8.2.4, 13.1.4, 13.2.2, 24.4, 24.5, 26.7, 26.8, 29.3.1, and 30.3.1; Boxes 25-1, 25-7)	High exposure of people, economic activity, and infrastructure in low-lying coastal zones, Small Island Developing States (SIDS), and other small islands Urban population unprotected due to substandard housing and inadequate insurance. Marginalized rural population with multidimensional poverty and limited alternative livelihoods Insufficient local governmental attention to disaster risk reduction		Death, injury, and disruption to livelihoods, food supplies, and drinking water Loss of common-pool resources, sense of place and identity, especially among indigenous populations in rural coastal zones	Interaction of rapid urbanization, sea level rise, increasing economic activity, disappearance of natural resources, and limits of insurance; burden of risk management shifted from the state to those at risk, leading to greater inequality
ii	Extreme precipitation and inland flooding (WGI AR5 FAQ 12.2; Sections 3.2.7, 3.4.8, 8.2.3, 8.2.4, 13.2.1, 25.10, 26.3, 26.7, 26.8, and 27.3.5; Box 25-8)	Large numbers of people exposed in urban areas to flood events, particularly in low-income informal settlements Overwhelmed, aging, poorly maintained, and inadequate urban drainage infrastructure and limited ability to cope and adapt due to marginalization, high poverty, and culturally imposed gender roles Inadequate governmental attention to disaster risk reduction		Death, injury, and disruption of human security, especially among children, elderly, and disabled persons	Interaction of increasing frequency of intense precipitation, urbanization, and limits of insurance; burden of risk management shifted from the state to those at risk, leading to greater inequality, eroded assets due to infrastructure damage, abandonment of urban districts, and the creation of high-risk/high-poverty spatial traps
iii	Novel hazards yielding systemic risks (WGI AR5 Section 11.3.2; Sections 8.1.4, 8.2.4, 10.2, 10.3, 12.6, 23.9, 25.10, 26.7, and 26.8)	Populations and infrastructure exposed and lacking historical experience with these hazards Overly hazard-specific management planning and infrastructure design, and/or low forecasting capability		Failure of systems coupled to electric power system, e.g., drainage systems reliant on electric pumps or emergency services reliant on telecommunications. Collapse of health and emergency services in extreme events	Interactions due to dependence on coupled systems lead to magnification of impacts of extreme events. Reduced social cohesion due to loss of faith in management institutions undermines preparation and capacity for response.
iv	Increasing frequency and intensity of extreme heat, including urban heat island effect (WGI AR5 Section 11.3.2; Sections 8.2.3, 11.3, 11.4.1, 13.2, 23.5.1, 24.4.6, 25.8.1, 26.6, and 26.8; Box CC-HS)	Increasing urban population of the elderly, the very young, expectant mothers, and people with chronic health problems in settlements subject to higher temperatures Inability of local organizations that provide health, emergency, and social services to adapt to new risk levels for vulnerable groups		Increased mortality and morbidity during periods of extreme heat	Interaction of changes in regional temperature extremes, local heat island, and air pollution, with demographic shifts Overloading of health and emergency services. Higher mortality, morbidity, and productivity loss among manual workers in hot climates
v	Warming, drought, and precipitation variability (WGI AR5 Section 11.3.2; Sections 7.3, 7.4, 7.5, 11.3, 11.6.1, 13.2.1, 13.2.2, 19.3.2, 19.4.1, 22.3.4, 24.4, 26.8, and 27.3.4)	Poorer populations in urban and rural settings are susceptible to resulting food insecurity; includes particularly farmers who are net food buyers and people in low-income, agriculturally dependent economies that are net food importers. Limited ability to cope among the elderly and female-headed households		Risk of harm and loss of life due to reversal of progress in reducing malnutrition	Interactions of climate changes, population growth, reduced productivity, biofuel crop cultivation, and food prices with persistent inequality and ongoing food insecurity for the poor increase malnutrition, giving rise to larger burden of disease. Exhaustion of social networks reduces coping capacity.

Continued next page →

Table 19-4 (continued)

No.	Hazard	Key vulnerabilities		Key risks	Emergent risks
vi	Drought (WGI AR5 Sections 12.4.1 and 12.4.5; Sections 3.2.7, 3.4.8, 3.5.1, 8.2.3, 8.2.4, 9.3.3, 9.3.5, 13.2.1, 19.3.2.2, and 24.4)	Urban populations with inadequate water services. Existing water shortages (and irregular supplies), and constraints on increasing supplies Lack of capacity and resilience in water management regimes including rural–urban linkages		Insufficient water supply for people and industry, yielding severe harm and economic impacts	Interaction of urbanization, infrastructure insufficiency, groundwater depletion
		Poorly endowed farmers in drylands or pastoralists with insufficient access to drinking and irregular water Limited ability to compensate for losses in water-dependent farming and pastoral systems, and conflict over natural resources Lack of capacity and resilience in water management regimes, inappropriate land policy, and misperception and undermining of pastoral livelihoods		Loss of agricultural productivity and/or income of rural people. Destruction of livelihoods, particularly for those depending on water-intensive agriculture. Risk of food insecurity	Interactions across human vulnerabilities: deteriorating livelihoods, poverty traps, heightened food insecurity, decreased land productivity, rural outmigration, and increase in new urban poor in low- and middle-income countries. Potential tipping point in rain-fed farming system and/or pastoralism
vii	Rising ocean temperature, ocean acidification, and loss of Arctic sea ice (WGI AR5 Section 11.3.3; Sections 5.4.2, 6.3.1, 6.3.2, 7.4.2, 9.3.5, 22.3.2.3, 24.4, 25.6, 27.3.3, 28.2, 28.3, 29.3.1, 30.5, and 30.6; Boxes CC-OA and CC-CR)	High susceptibility of warm water coral reefs and respective ecosystem services for coastal communities; high susceptibility of polar systems, e.g., to invasive species Susceptibility of coastal and SIDS fishing communities depending on these ecosystem services; and of Arctic settlements and culture		Loss of coral cover, Arctic species, and associated ecosystems with reduction of biodiversity and potential losses of important ecosystem services. Risk of loss of endemic species, mixing of ecosystem types, and increased dominance of invasive organisms	Interactions of stressors such as acidification and warming on calcareous organisms enhancing risk
viii	Rising land temperatures, changes in precipitation patterns, and frequency and intensity of extreme heat (WGI AR5 Section 11.3.2.5; Sections 4.3.4, 19.3.2.1, 22.4.5.6, and 27.3.2.1; FAQs 4.5 and 4.7; Boxes 23-1 and CC-WE)	Susceptibility of societies to loss of provisioning, regulation, and cultural services from terrestrial ecosystems Susceptibility of human systems, agro-ecosystems, and natural ecosystems to (1) loss of regulation of pests and diseases, fire, landslide, erosion, flooding, avalanche, water quality, and local climate; (2) loss of provision of food, livestock, fiber, bioenergy; (3) loss of recreation, tourism, aesthetic and heritage values, and biodiversity		Reduction of biodiversity and potential losses of important ecosystem services. Risk of loss of endemic species, mixing of ecosystem types, and increased dominance of invasive organisms	Interaction of social-ecological systems with loss of ecosystem services upon which they depend



distribution and storage systems, increase risk. Especially vulnerable are those with limited ability to compensate for losses in water-dependent farming and pastoral systems, as well as those subject to conflict over natural resources. In addition, insufficient supply of water due to droughts and institutional vulnerabilities (e.g., lack of state capacities, conflicts) for both industry and urban populations lacking running water, yielding severe economic impacts and other harms (WGI AR5 Sections 12.4.1, 12.4.5; Sections 3.2.7, 3.4.8, 3.5.1, 8.2.3-4, 9.3.3, 9.3.5, 13.2.1, 19.3.2.2, 24.4). [RFC 2 and 3]

vii) *Risk of loss of marine and coastal ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for coastal livelihoods, especially for fishing communities in the tropics and the Arctic*. These resources are especially at risk due to rising water temperature and the increase of stratification and ocean acidification. Loss of Arctic sea ice and degradation of coral reefs, as well as other natural barriers, presents a high risk to ecosystem services where many people are exposed to coastal hazards and also depend on coastal resources for livelihoods, such as Alaska, the Philippines, and Indonesia (WGI AR5 Section 11.3.3; Sections 5.4.2, 6.3.1-2, 7.4.2, 9.3.5, 22.3.2.3, 24.4, 25.6, 27.3.3, 28.2-3, 29.3.1, 30.5-6; Boxes CC-OA, CC-CR). [RFC 1, 2, and 4]

viii) *Risk of loss of terrestrial and inland water ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for livelihoods*. Biodiversity and terrestrial ecosystem services are important for rural and urban communities globally. These services are at risk due to rising temperatures, changes in precipitation patterns, and extreme weather events. Risks are high for communities whose livelihoods depend on provisioning services. Human and natural systems are susceptible to loss of provisioning services such as food and fiber, regulating services such as water quality, fire, and erosion, and cultural services such as aesthetic values and tourism (WGI AR5 Section 11.3.2.5; Sections 4.3.4, 19.3.2.1, 22.4.5.6, 27.3.2.1; Boxes 23-1, CC-WE; FAQs 4.5, 4.7). [RFC 1, 3 and 4]

An important common characteristic of all key risks associated with anthropogenic climate change is that they are determined by hazards due to changing climatic conditions on the one hand and the vulnerability of exposed societies, communities, and social-ecological systems, for

example, in terms of livelihoods, infrastructure, ecosystem services and management/governance systems on the other (see Table 19-4). The compilation of key risks underscores that effective adaptation and risk reduction measures would address all three components of risk (*high confidence*).

19.6.2.2. The Role of Adaptation and Alternative Development Pathways

As discussed in Section 19.2.4, the identification of key risks depends in part on the underlying socioeconomic conditions assumed to occur in the future, which can differ widely across alternative development pathways. This section assesses literature that compares impacts across development pathways, compares the contributions of anthropogenic climate change and socioeconomic development (through changes in vulnerability and exposure) to climate-related impacts, and examines the potential for adaptation to reduce those impacts. Based on this assessment, risks vary substantially across plausible alternative development pathways and the relative importance of development and climate change varies by sector, region, and time period, but in general both are important to understanding possible outcomes (*high confidence*). In some cases, there is substantial potential for adaptation to reduce risks, with development pathways playing a critical role in determining challenges to adaptation, including through their effects on ecosystems and ecosystem services (Rothman et al., 2014).

Direct comparison of impacts across alternative development pathways shows, for example, that socioeconomic conditions are an important determinant of the impacts of climate change on food security, water stress, and the consequences of extreme events and sea level rise. The additional effect of climate change and CO_2 fertilization on the number of people at risk from hunger by 2080 generally spans a range of ± 10 to 30 million across the four marker SRES scenarios, each of which assumes different socioeconomic futures. However, in a scenario (A2) with high population growth and slow economic growth, this effect becomes as high as 120 to 170 million in some analyses (Schmidhuber and Tubiello, 2007). Similarly, the number of people exposed to water scarcity in a global study is sensitive to population growth assumptions (Gosling and Arnell, 2013), as are projected water resources in the Middle East under an A1B climate change scenario (Chenoweth et al., 2011). Assessments of the risks from river flooding depend on alternative future population and land use assumptions (Bouwer et al., 2010; te Linde et al., 2011), and sea level rise impacts depend on development pathways through their effect on the exposure of both the population and economic assets to coastal impacts, as well as on the capacity to invest in protection (Anthoff et al., 2010).

The view that development pathways are an important determinant of risk related to climate change impacts is further supported by two other types of studies: those that examine the vulnerability of subgroups of the current population, and those that compare the relative importance of climate and socioeconomic changes to future impacts. The first type finds that variation in current socioeconomic conditions explains some of the variation in risks associated with climate and climate change, supporting the idea that alternative development pathways, which describe different patterns of change in these conditions over time, should influence the future risks of climate change. For example, socioeconomic conditions have been found to be a key determinant of risks to low-income households due to climate change effects on agriculture (Ahmed et al., 2009; Hertel et al., 2010), to sub-populations due to exposure to heterogeneous regional climate change (Diffenbaugh et al., 2007), and to low-income coastal populations due to storm surges (Dasgupta et al., 2009). Assessments of environmentally induced migration have concluded that migration responses are mediated by a number of social and governance characteristics that can vary widely across societies (Warner, 2010; see Sections 12.4, 19.4.2.1).

The second type of study finds that, within a given projection of future climate change and change in socioeconomic conditions, typically both are important to determining risks. In fact, the effect of the physical impacts of climate change on globally aggregated changes in food consumption or risk of hunger have been found to be small relative to changes in these metrics driven by socioeconomic development alone (Schmidhuber and Tubiello, 2007; Nelson et al., 2010; Wiltshire et al., 2013). Similarly, future population growth is found to be an equally (Murray et al., 2012) or more (Fung et al., 2011; Schewe et al., 2013) important determinant of globally aggregated water stress as the level of climate change, and population growth, economic growth, and urbanization are expected to largely drive potential future damages to coastal cities due to flooding (*high confidence*; Section 5.4.3.1; Hallegatte et al., 2013) and to be important determinants of damages from tropical cyclones (Bouwer et al., 2007; Pielke Jr., 2007; Mendelsohn et al., 2012). At the regional level, socioeconomic development has also been found to be equally or more important than climate change to impacts in Europe due to sea level rise, through coastal development (Hinkel et al., 2010); heat stress, especially when acclimatization (Watkiss and Hunt, 2012) or aging (Lung et al., 2013) is taken into account; and flood risks, through exposure due to land use and distributions of buildings and infrastructure (Feyen et al., 2009; Bouwer et al., 2010). Climate change was the dominant driver of flood risks in Europe when future changes in the value of buildings and infrastructure at risk were excluded from the analysis (te Linde et al., 2011; Lung et al., 2013) or when biophysical impacts such as stream discharge, rather than its consequences, were assessed (Ward et al., 2011).

Land use is another socioeconomic factor that can affect risks in addition to climate change, but until recently few studies have addressed the combined impacts of climate change and land use on ecosystems (Warren et al., 2011). Studies including multiple drivers of extinction find that although land use change remains the dominant driver out to 2100, climate change is the next most important driver (Sala et al., 2000; Millenium Ecosystem Assessment, 2005b). A study of land bird extinction risk found some sensitivity to four alternative land use scenarios, but by 2100 risk was dominated by the climate change scenario (Şekercioğlu, 2008). A study of European land use found that while land use outcomes were more sensitive to the assumed socioeconomic scenario, consequences for species depended more on the climate scenario (Berry et al., 2006).

Explicit assessments of the potential for adaptation to reduce risks have indicated that there is substantial scope for reducing impacts of several types, but the capacity to undertake this adaptation is dependent on underlying development pathways. Assessments of the impacts of

sea level rise, for example, show that if development pathways allow for substantial investment of resources in adaptation through coastal protection, as opposed to accommodation or abandonment strategies, reducing impacts by investing in coastal protection can be an economically rational response for large areas of coastline globally (Nicholls et al., 2008a,b; Anthoff et al., 2010; Nicholls and Cazenave, 2010; Hallegatte et al., 2013) and in Europe (Bosello et al., 2012b). For the specific case of sea level rise impacts in Europe, adaptation in the form of increasing dike heights and nourishing beaches, at a cost reaching about €3 billion per year by 2100, was found to reduce the number of people affected by coastal flooding in 2100 from hundreds of thousands to a few thousand per year depending on the socioeconomic and sea level rise scenario (A2 vs. B1), and total economic damages from about €17 billion to about €2 billion per year (Hinkel et al., 2010). In contrast, in some areas with higher current and anticipated future vulnerability such as low-lying island states and parts of Africa and Asia, impacts are expected to be greater and adaptation more difficult (Nicholls et al., 2011).

Similarly, the risk to food security in many regions could be reduced if development pathways increase the capacity for policy and institutional reform, although most impact studies have focused on agricultural production and accounted for adaptation to a limited and varying degree (Lobell et al., 2008; Nelson et al., 2009; Ziervogel and Ericksen, 2010). A study of response options in sub-Saharan Africa identified some scope for adapting to climate change associated with a global warming of 2°C above preindustrial levels (Thornton et al., 2011), given substantial investment in institutions, infrastructure, and technology, but was pessimistic about the prospects of adapting to a world with 4°C of warming (Thornton et al., 2011; see also Section 19.7.1). Improved water use efficiency and extension services have been identified as the highest priority agricultural adaptation options available in Europe (Iglesias et al., 2012), and a potentially large role for expanded desalination has been identified for the Middle East (Chenoweth et al., 2011).

19.6.3. Updating Reasons for Concern

The RFCs are the relationship between global mean temperature increase and five categories of impacts that were introduced in the IPCC TAR (Smith et al., 2001) in order to facilitate interpretation of Article 2

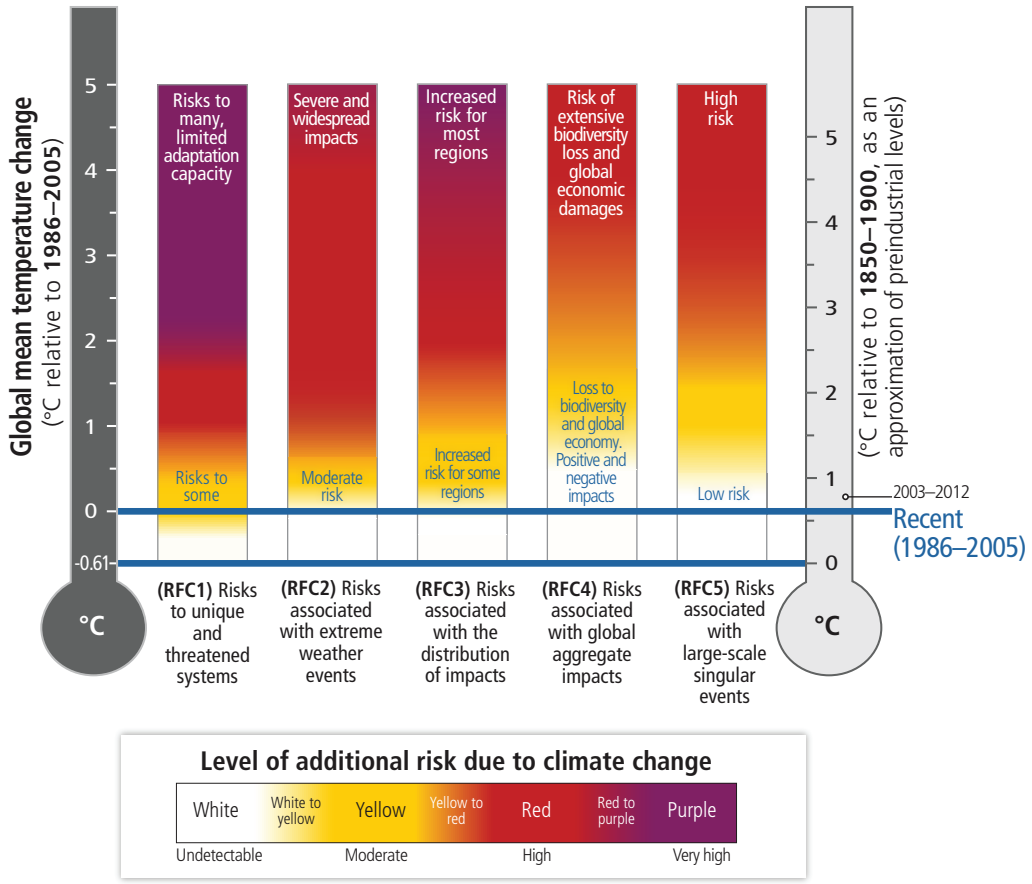


Figure 19-4 | The dependence of risk associated with the Reasons for Concern (RFCs) on the level of climate change, updated from the Third Assessment Report and Smith et al. (2009). The color shading indicates the additional risk due to climate change when a temperature level is reached and then sustained or exceeded. The shading of each ember provides a qualitative indication of the increase in risk with temperature for each individual "reason." Undetectable risk (white) indicates no associated impacts are detectable and attributable to climate change. Moderate risk (yellow) indicates that associated impacts are both detectable and attributable to climate change with at least *medium confidence*, also accounting for the other specific criteria for key risks. High risk (red) indicates severe and widespread impacts, also accounting for the other specific criteria for key risks. Purple, introduced in this assessment, shows that very high risk is indicated by all specific criteria for key risks. Comparison of the increase of risk across RFCs indicates the relative sensitivity of RFCs to increases in GMT. In general, assessment of RFCs takes autonomous adaptation into account, as was done previously (Smith et al., 2001, 2009; Schneider et al., 2007). In addition, this assessment took into account limits to adaptation in the case of RFC1, RFC3, and RFC5, independent of the development pathway. The rate and timing of climate change and physical impacts, not illustrated explicitly in this diagram, were taken into account in assessing RFC1 and RFC5. Comments superimposed on RFCs provide additional details that were factored into the assessment. The levels of risk illustrated reflect the judgments of Chapter 19 authors.

(Section 1.2.2; Box 19-2). In AR4, new literature related to the five RFCs was assessed, leading in most cases to confirmation or strengthening of the judgments about their relevance to defining dangerous anthropogenic interference based on evidence that some impacts were already apparent, higher likelihoods of some climate-related hazards, and improved identification of currently vulnerable populations (Schneider et al., 2007; Smith et al., 2009).

RFCs are related to the framework of key risks, climate-related hazards, and vulnerabilities used in this chapter because each RFC is understood to represent a broad category of key risks to society or ecosystems associated with a specific type of hazard (extreme weather events, large-scale singular events), system at risk (unique and threatened systems), or characteristic of risk to social-ecological systems (global aggregate impacts on those systems, distribution of impacts to those systems). For example, the RFC for extreme weather events implies a concern for risks to society and ecosystems posed by extreme events, rather than a concern for extreme events per se. Accordingly, in this chapter we have reworded the definition of RFCs to emphasize risk.

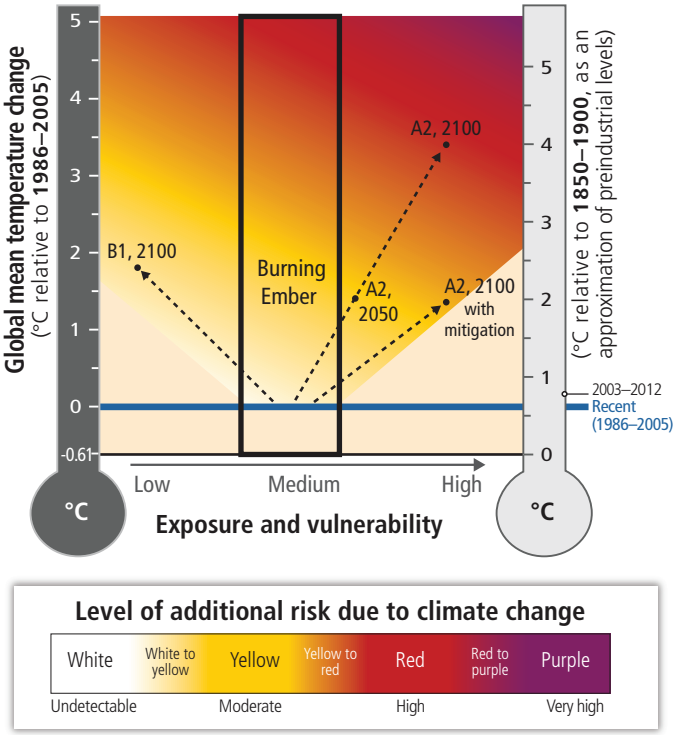


Figure 19-5 | Illustration of the dependence of risk associated with a Reason for Concern (RFC) on the level of climate change and exposure and vulnerability (E&V) of society. This figure is schematic; the degree of risk associated with particular levels of climate change or E&V has neither been based on a literature assessment nor associated with a particular RFC (the "burning ember" in the figure refers generically to any of the embers in Figure 19-4). The E&V axis is relative rather than absolute. "Medium" E&V indicates a future development path in which E&V changes over time are driven by moderate trends in socioeconomic conditions. "Low" and "High" E&V indicate futures that are substantially more optimistic or pessimistic, respectively, regarding exposure and vulnerability. Judgments made in other burning ember diagrams of the RFCs (Smith et al., 2001, 2009) including Figure 19-4, which do not explicitly take changes in E&V into account, are consistent with Medium future E&V. Arrows and dots illustrate the use of Special Report on Emission Scenarios (SRES)-based literature to locate particular impact or risk assessments on the figure according to the evolution of climate and socioeconomic conditions over time. This figure does not explicitly address issues related to the rates of climate change or when impacts might be realized.

In this section we assess new literature related to each of the RFCs, concluding that, compared to judgments presented in AR4 and in Smith et al. (2009), levels of risk associated with extreme weather events and distribution of impacts can be assessed with higher confidence and are higher for large temperature rise than previously assessed; risks associated with global aggregate impacts are similar to AR4 and Smith et al (2009) and confidence in the assessment unchanged; and risks to unique and threatened systems and those associated with large-scale singular events are higher above 2°C (compared to a 1986–2005 baseline) than assessed previously. These judgments are illustrated in Figure 19-4, an updated version of the "burning embers" diagram that describes how the additional risk due to climate change for each RFC changes with increasing GMT. We retain the color scheme employed in previous versions of this figure (Smith et al., 2001, 2009) with some refinement. White, yellow, and red indicate undetectable, moderate, and high additional risk, respectively. Risk is low in the transition between white and yellow, and substantial in the transition between yellow and red. We add a new color (purple) indicating very high risk as elaborated below.

The following subsections assess risks for each RFC and locate transitions between colors using the criteria for key risks as a guide (Section 19.2.2.2). The transition from white to yellow is partly defined by the GMT at which there is at least *medium confidence* that impacts associated with a given risk are both detectable and attributable to climate change, while also accounting for the magnitude of the risk. We draw on Section 18.6.4 to inform the placement of this transition relative to recent GMT. The transition from yellow to red is defined by increasing magnitude (including pervasiveness) or likelihood of impacts, with high risk (red color) defined as risk of severe and widespread impacts that is judged to be high on one or more criteria for assessing key risks (Section 19.2.2.2). Purple, introduced in this assessment, shows that very high risk is indicated by all specific criteria for key risks, including limited ability to adapt. As was true in the TAR and Smith et al. (2009), transitions are fuzzy owing to uncertainties in a variety of factors determining the relation between GMT and risk, including the rate of climate change, the time at which the temperature is reached, and the extent and agreement of the evidence base in the literature.

We also clarify the concept of RFCs: because risks depend not only on physical impacts of climate change but also on exposure and vulnerability of societies and ecosystems to those impacts, RFCs as a reflection of those risks depend on both factors as well (see also Section 19.1).

19.6.3.1. Variations in RFCs across Socioeconomic Pathways

The determination of key risks as reflected in the RFCs has not previously been distinguished across alternative development pathways. In the TAR and AR4, RFCs took only autonomous adaptation into account (Smith et al., 2001; Schneider et al., 2007; WGII AR4 Chapter 19). However, the RFCs represent risks that are determined by both climate-related hazards and the vulnerability and exposure of social and ecological systems to climate change stressors. Figure 19-5 illustrates this dependence on vulnerability and exposure in a modified version of

the burning embers diagram. Current literature is not sufficient to support confident assessment of specific RFCs using this approach.

As literature accumulates, it could inform new versions of this figure applied to specific RFCs. For example, studies that employ particular scenarios of socioeconomic conditions could be categorized according to the levels of vulnerability represented by those scenarios (van Vuuren et al., 2012) to locate results along the horizontal axes, while climate conditions assumed in those studies would locate results along the vertical axis. As with previous versions of the burning embers, however, this new figure does not explicitly address issues related to rates of climate change or to when impacts might be realized. The updates of RFCs in 19.6.3.2 to 19.6.3.6 that follow (and are illustrated in Figure 19-4) do not account for differences in vulnerability across development paths; rather, they are based on the same assessment framework as used in AR4 and Smith et al. (2009), but with additional elaboration.

19.6.3.2. Unique and Threatened Systems

Unique and threatened systems include a wide range of physical, biological, and human systems that are restricted to relatively narrow geographical ranges and are threatened by future changes in climate (Smith et al., 2001). Where consequences are *irreversible* and *importance* to society and other systems is high, the potential for loss of or damage to such systems constitutes a key risk. AR4 stated with *high confidence* that a warming of up to 2°C above preindustrial levels would result in significant impacts on many unique and vulnerable systems and would increase the endangered status of many threatened species, with increasing adverse impacts (and increasing confidence in this conclusion) at higher temperatures (Schneider et al., 2007). Since AR4, there is a growing body of literature suggesting that the number of threatened systems and species is greater than previously thought.

Chapters 4, 22, 23, 24, 25, 26, and 27 highlight areas where unique and threatened systems are particularly vulnerable to climate change. Evidence for severe and widespread impacts to humans and social systems, ecosystems, and species in polar regions as warming progresses has continued to accrue (Sections 4.3.3.4, 28.2). Projections of Arctic sea ice melt rates have increased since AR4 (WGI AR5 Section 12.4.6), increasing risks to the Inuit and the sea ice-dependent ecosystems upon which they subsist. CMIP5 model runs for September with all RCPs show substantial additional losses of Arctic Ocean ice for a global warming of 1°C relative to 1986–2005 and a nearly ice-free Arctic Ocean for global warming greater than 2°C (WGI AR5 Figure 12.30). Furthermore, a nearly ice-free Arctic Ocean in September before mid-century is *likely* under RCP8.5 (*medium confidence*; WGI AR5 Section 12.4.6).

Coral reef ecosystems are still considered amongst the most vulnerable of unique marine systems (Sections 5.4.2.4, 19.3.2.4), with corals' evolutionary responses being outpaced by climate change (Hoegh-Guldberg, 2012) resulting in projections of extensive reef decline throughout the 21st century. Globally, large-scale reef dissolution may occur if CO_2 concentrations reach 560 ppm (Section 5.4.2.4) due to the combined effects of warming and ocean acidification. Even if global temperature rise in the 2090s is constrained to 1.2 to 2.0°C above preindustrial levels (WGI AR5 Table 12.3, RCP2.6), and assuming rapid adaptation rates in corals, 9 to 60% of reefs are projected to be subject to long-term degradation, while 30 to 88% of reefs are projected to eventually degrade if global temperature rises in the 2090s by 1.9 to 2.9°C above preindustrial levels (RCP4.5; Box CC-CR; temperatures from WGI AR5 Table 12.3). Loss of corals and mangrove ecosystems would endanger the livelihoods of unique human communities and cause economic damage (Section 4.3.3 for global discussion; Sections 22.3.2.3, 24.4.3, 25.6 for Africa, Asia, and Australia; Section 26.4 for North America; Section 27.3.3.1 for South America).

There is a large and increasing amount of evidence for escalating risks of species range loss, extirpation, and extinction based on studies for global temperatures exceeding 2°C above preindustrial levels (1.4°C above 1986–2005; Warren et al., 2011; Şekercioğlu et al., 2012, Foden et al., 2013; Warren et al., 2013a). An assessment of 16,857 species (Foden et al., 2013) found that with approximately 2°C of warming above preindustrial (A1B, 2050s), 24 to 50% of the birds, 22 to 44% of the amphibians, and 15 to 32% of the corals were highly vulnerable to climate change defined as having high sensitivity, high exposure, and low adaptive capacity.

An increasing number of threatened systems has been identified, in the form of projected species range losses and extinction risks, although without yet tying risks to specific levels of warming. Evidence of climate risks to unique mountain ecosystems and their numerous endemic alpine species has continued to accrue in Europe, Asia, Australia, and South America (Sections 23.6.4, 24.4.2.3, 25.6.1, 27.3.2.1). Siberian, tropical, and desert ecosystems in Asia (Section 24.4.2.3), Africa (Warren et al., 2013a), and Mediterranean areas in Europe (Klausmeyer and Shaw, 2009; Maiorano et al., 2011), the Queensland rainforest, Kakadu National Park, and the southwestern region of Australia (Section 25.6.1), Amazonian ecosystems in South America (Foden et al., 2013; Warren et al., 2013a), and freshwater ecosystems in Africa (specifically Ethiopia, Malawi, Mozambique, Zambia, and Zimbabwe) (Section 22.3.2.2) are particularly at risk, as are the Fynbos and succulent Karoo areas of South Africa (Midgley and Thuiller, 2011; Kuhlmann et al., 2012; Huntley and Barnard, 2012) and dune systems in temperate climates (Section 23.6.5). Recent research has identified risks to highly biodiverse tropical wet and dry forests (Sections 4.3.3, 24.4.2.3; Kearney et al., 2009, Wright et al., 2009; Toms et al., 2012) and tropical island endemics (Fordham and Brook, 2010). Globally amphibians were found to be the most vulnerable of vertebrate taxa (Stuart et al., 2004; Brito, 2008; Rohr and Raffel, 2010; Liu et al., 2013; Warren et al., 2013a).

Owing to higher projections of sea level rise than in AR4 (WGI AR5 Sections 13.5-7), risk of partial inundation of small island states has increased.

"Since AR4, almost all glaciers worldwide have continued to shrink as revealed by the time series of measured changes in glacier length, area, volume and mass (*very high confidence*)" (WGI AR5 Chapter 4 ES). There is substantial new evidence that, across most of Asia, glaciers have been shrinking, except in some areas in the Karakorum and Pamir (Section 18.5.3). In the Andes, glacier loss threatens to reduce the water and electricity supplies of large cities and hydropower projects, as well as the agricultural and tourism sectors (Sections 27.3.1.1-2, 27.6.1; Table 27-3). Model simulations show a large projected loss of glacier ice volume in central Asia by end of the century: in particular, estimates for

RCP8.5 and RCP4.5 suggest the potential for loss of most of the 2006 ice volume (Section 24.9.2). Loss of glacial cover has been projected to significantly reduce water supplies in meltwater-dependent arid regions (Kaser et al., 2010), potentially threatening the food security of 60 million people in the Brahmaputra and Indus basins by the 2050s (Immerzeel et al., 2010). However, recent work has suggested the glacier melt rates in two Himalayan watersheds, Baltoro and Langtang, were previously overestimated and, since precipitation is projected to concurrently increase, runoff may actually rise until 2050 in these particular watersheds (Immerzeel et al., 2013). Large uncertainties in projections of Himalayan ice cover and runoff dynamics remain (Bolch et al., 2012).

In Figure 19-4, we locate the transition to moderate risk (white to yellow) below recent global temperatures because there is at least *medium confidence* in attribution of a major role for climate change for impacts on at least one each of ecosystems, physical systems, and human systems (Section 18.6.4). A transition to purple is located around 2°C above 1986–2005 levels to reflect the very high risk to species and ecosystems projected to occur beyond that level as well as limited ability to adapt to impacts on coral reef systems and on Arctic sea ice-dependent systems (Chapters 4, 5, 6, 28) if that level of warming were exceeded (*high confidence*). A transition to red is located around 1°C above 1986–2005 levels, midway between current temperature and the transition to purple, indicating the increasing risk to unique and threatened systems, including Arctic sea ice and coral reefs, as well as threatened species as temperature increases over this range.

19.6.3.3. Extreme Weather Events

Extreme weather events (e.g., heat waves, intense precipitation, drought, tropical cyclones) trigger impacts that can pose key risks to societies that are exposed and vulnerable (Lavell et al., 2012). With regard to the physical hazard aspect of risk, AR5 assesses a higher likelihood of attribution of heat waves and extreme hot days and nights to human activity than AR4. WGI AR5 states, "We assess that it is *very likely* that human influence has contributed to the observed changes in the frequency and intensity of daily temperature extremes on the global scale since the mid-20th century" (WGI AR5 Section 10.6.1.1) and "it is *likely* that human influence has substantially increased the probability of occurrence of heat waves in some locations" (WGI AR5 Section 10.6.2). WGI finds *medium confidence* in attribution of intensification of heavy precipitation over land areas with sufficient data (WGI AR5 Section 10.6.1.2), and "*low confidence* in detection and attribution of changes in drought over global land areas" (WGI AR5 Section 10.6.1.3) and global changes in tropical cyclone activity (WGI AR5 Section 10.6.1.5) to human influence. There is *high confidence* in attribution of impacts of weather extremes (as opposed to the physical hazards alone) on coral reef systems (Sections 18.6.4, 19.6.3.2; Table 18-10), with evidence for impact attribution limited and highly localized otherwise.

The likelihood of projected 21st century changes in extremes has not changed markedly since AR4 (WGI AR5 Chapters 10, 12), but for the first time near-term changes (for the period 2016–2035 relative to 1986–2005) are assessed (WGI AR5 Chapter 1), a period during which the increase in the model and scenario averaged GMT is projected to remain below 1°C relative to 1986–2005 (WGI AR5 Figure 11.8; WGI AR5 Section 11.3.6.3). Among the conclusions are, "In most land regions the frequency of warm days and warm nights will *likely* increase in the next decades, while that of cold days and cold nights will decrease" (WGI AR5 Chapter 11 ES). Specifically, about 15% of currently observed maximum daily temperatures exceed the historical 90th percentile values (rather than the historical 10%) and, by about 2035, 25 to 30% of daily maximums are projected to exceed the historical 90th percentile value (WGI AR5 Figure 11.17). WGI also notes that "Models project near-term increases in the duration, intensity and spatial extent of heat waves and warm spells" (WGI AR5 Chapter 11 ES; WGI AR5 Table SPM.1). With regard to extreme precipitation events, WGI finds "The frequency and intensity of heavy precipitation events over land will *likely* increase on average in the near term. However, this trend will not be apparent in all regions because of natural variability and possible influences of anthropogenic aerosols" (WGI AR5 Chapter 11 ES). In addition, SREX (IPCC, 2012a, Figure SPM.4B) projects a reduction in return period for historical once-in-20-year precipitation events globally (land only) to about once-in-14-year or less by 2046–2065.

With regard to the vulnerability and exposure aspects of risk, SREX reviewed literature on the relationship between changes in these factors and the risk of extreme events (IPCC, 2012a, Sections 4.5.4, 4.5.6). Increases in local vulnerability and exposure to extreme precipitation can lead to a disproportionate increase in overall risk (IPCC, 2012a, Sections 4.3.5.1, 9.2.8; Douglas et al., 2008; Douglas, 2009; Hallegate et al., 2011; Ranger, 2011). For example, growth of megacities both concentrates exposure and vulnerability and can generate "synchronous failure" that spreads beyond the immediate vicinity of extreme events. Megacities increase nighttime temperature extremes via the urban heat island effect (Section 8.2.3.1; IPCC, 2012a, Sections 4.3.5.1, 4.4.5.2) while also enhancing exposure to high air pollution levels (IPCC, 2012a, Sections 4.3.5.1, 9.2.1.2.3; Fang et al., 2013) and consequent health effects (Sections 11.5.3.2, 11.5.3.4), with widespread impacts by mid-century in some studies. Densely populated areas of East and South Asia and North America are projected to be especially affected by climate-related air pollution (Fang et al., 2013).

Projections of the global socioeconomic (Mendelsohn et al., 2012) impact of tropical cyclones demonstrate increasing risk due to interactions of increasing storm intensity with exposure. Hazard projection suggests a disproportionate increase in exposure to tropical cyclone risk with increasing temperature at New York City due to combined effects of storm intensification and sea level rise (Lin et al., 2012). Other studies (Jongman et al., 2012; Hallegate et al., 2013; Preston, 2013) project increasing coastal flood risk due to increasing exposure, although the first two do not disaggregate to specific types of extreme events. Taken together, this evidence supports a conclusion of disproportionate increase in risk associated with extreme events as temperature, and in many cases, exposure and vulnerability increase as well.

Based on the above assessments of the physical hazard alone, we find increased confidence in the AR4 assessment of the risk from extreme weather events. Based on the attribution of heat and precipitation extremes to anthropogenic climate change, the attribution to climate change of impacts of climate extremes on one unique and threatened system, and the current vulnerability of other exposed systems, we assign a yellow level of risk at recent temperatures in Figure 19-4 (*high*

confidence), consistent with Smith et al. (2009). We assign a transition to red beginning below 1°C compared to 1986–2005 (also consistent with Smith et al. (2009)) based primarily on the *magnitude* and *likelihood* and *timing* (see Section 19.2.2.2) of the projected change in hazard of extreme weather events, indicating that impacts will become more severe and widespread over the next few decades (*medium confidence*). Risks associated with some types of extreme events (e.g., extreme heat) increase further at higher temperatures (*high confidence*).

19.6.3.4. Distribution of Impacts

The distribution of impacts is a category of climate change consequences that includes key risks to particular societies and social-ecological systems that may be disproportionately affected due to unequal distribution of hazards, exposure, or vulnerability. AR4 concluded that there is *high confidence* that low-latitude, less-developed areas are generally at greatest risk and found that, because vulnerability to climate change is also highly variable within countries, some population groups in developed countries are also highly vulnerable even to a warming of less than 2°C above 1990–2000 (Schneider et al., 2007). These conclusions remain valid and are now supported by a limited number of impact studies that explicitly consider differences in socioeconomic conditions that affect vulnerability across regions or populations (Mougou et al., 2011; Müller et al., 2011; Gosling and Arnell, 2013; Schewe et al., 2013). Furthermore, we have increased confidence in the AR4 assessment of the risk arising in the near term from the distribution of impacts from extreme weather events because, by their very nature, these events change in a locally and temporally variable fashion with, for example, a larger change in extreme temperatures at higher latitudes (IPCC, 2012a, Figure SPM.4A).

Impacts of climate change on food security depend on both production and non-production aspects of the food system, including not just yield effects but also changes in the amount of land in production and adjustments in trade patterns (Section 7.1.1). Effects on prices are often taken as an indicator of impacts on food security, and the combined effect of climate and CO_2 change (but ignoring O_3 and pest and disease impacts) appears *about as likely as not* to increase prices by 2050, with few new studies examining prospects at longer time horizons (Section 7.4.4). Most studies have focused on geographical differences in the effects of climate change on crop yields. With regard to such distributional consequences, yields of maize and wheat begin to decline with about 1°C to 2°C of local warming in the tropics, with or without adaptation taken into account (Figure 7-4). Temperate maize and tropical rice yields are less clearly affected at these temperatures, but significantly affected with local warming of 3 to 5°C particularly without adaptation (based on studies with various baselines, see Section 7.3.2.1). These data confirm AR4 findings that even small warming will decrease yields in low-latitude regions (*medium evidence*, *high agreement*; Section 7.3.2.1.1), and increase the risk assigned to yields in mid- to high-latitude regions (compared to AR4), suggesting that temperate wheat yield decreases are *about as likely as not* for moderate warming.

Risks of climate change related to freshwater systems, such as water scarcity and flooding, increase with global mean temperature rise (*medium evidence*, *high agreement*; Chapter 3 ES; Table 3-2). Climate change is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions (*high agreement*, *robust evidence*; Section 3.5; Chapter 3 ES). One study using multiple climate and hydrological models to simulate impacts of scenario RCP8.5 and Shared Socioeconomic Pathway 2 (SSP2) project that global warming of 1.7°C above preindustrial will reduce water resources by more than one standard deviation, or by more than 20%, for 8% of the global population, while for warming of 2.7°C above preindustrial this increases to 14% (model range 10 to 30%), and for warming of 3.7°C above preindustrial it reaches a mean of 17% across models (Schewe et al., 2013). In addition, in another study (Gosling and Arnell, 2013), climate change amplifies water scarcity by 30 to 40% for 1.7 to 2.7°C of warming, with around 40% of the global population under increased water stress. In one model, exposure to water scarcity increases steeply up to 2.3°C above preindustrial in North and East Africa, Arabia, and South Asia (Gosling and Arnell, 2013). In Africa water resources risks are "medium-high" at 2°C and "high-very high" at 4°C (Table 22-6). Model projections generally agree that discharge will decrease in the Mediterranean and in large parts of North and South America (Schewe et al., 2013). However, there are opportunities for adaptation in the water resources sector, particularly for municipal water supply (Section 3.6).

The first global scale analysis of climate change impacts on almost 50,000 species of plants and animals has highlighted that risks are not distributed equally, with sub-Saharan Africa, Central America, Amazonia, and Australia at risk for plants and animals, and North Africa, Central Asia, and southeastern Europe for many plants (Warren et al., 2013a). A traits-based analysis of more than 16,000 species identified Amazonia and Mesoamerica as being at risk for birds and amphibians; central Eurasia, the Congo Basin, the Himalayas, and Sundaland for birds; and the Coral Triangle region for corals (Foden et al., 2013).

In summary, since AR4, new evidence has emerged highlighting the *magnitude* of risk for particular regions, for example, in relation to the potential for regional impacts on ecosystems (see Section 19.6.3.2), megadeltas (see Section 8.2.3.3; Chapter 5), and agricultural systems, which is exacerbated by the potential for changes in the monsoon systems (see WGI AR5 Sections 12.5.5, 14.2). Overall there is increased evidence that low-latitude and less developed areas generally face greater risk than higher latitude and more developed countries (Smith et al., 2009). At the same time, there has been an increase in appreciation for vulnerability (e.g., to extreme events) in developed countries, especially, localized issues of differential vulnerability in particular areas of the developed world (IPCC, 2012a, Section 2.5.1.2).

Regionally differentiated impacts on crop production have been detected and attributed to climate change with *medium* to *high confidence* (Section 18.4.1.1), and we interpret this as an early warning sign of attributable impacts on food security. For this reason, as well as for reasons of *timing* and *likelihood* and *magnitude* of these risks, we assign a yellow level of risk at recent temperatures in Figure 19-4. Based on risks to regional crop production and water resources the transition from yellow to red is assessed to occur between 1°C and 2°C above the 1986–2005 global mean temperature (*medium confidence*). Both assessments are consistent with Smith et al. (2009). Furthermore, given evidence that agronomic adaptations would be more than offset for tropical wheat and maize where increases in local temperature of more

than 3°C above preindustrial occur (*limited evidence*, *medium agreement*; Chapter 7 ES; Section 7.5.1.1.1; Figure 7-4), the intensity of red increases nonlinearly toward purple in recognition of the temperature sensitivity of crop productivity and limited efficacy of agronomic adaptation above 2°C compared to 1986–2005.

19.6.3.5. Global Aggregate Impacts

The RFC pertaining to aggregate impacts includes risks that are aggregated globally into a single metric, such as monetary damages, lives affected, lives lost, or species or ecosystems lost. Estimates of the aggregate, economy-wide risks of climate change since AR4 continue to exhibit a *low level of agreement*. Studies at the sectoral level have been refined with new data and models, and have assessed new sectors.

AR4 stated with *medium confidence* that approximately 20 to 30% of the plant and animal species assessed to date are likely at increasing risk of extinction as global mean temperatures exceed a warming of 2°C to 3°C above preindustrial levels (Fischlin et al., 2007). There is *high confidence* that climate change will contribute to increased extinction risk for terrestrial, freshwater, and marine species over the coming century (Sections 4.3.2.5, 30.5; Box CC-CR). Since AR4 a substantial amount of additional work has been done, looking at many more species and using new and/or improved modeling and traits-based techniques, strengthening the evidence of increasing risk of extinction with increasing temperature (e.g., Lenoir et al., 2008; Amstrup et al., 2010; Hunter et al., 2010; Bálint et al., 2011; Pearman et al., 2011; Barnosky et al., 2012; Bellard et al., 2012; Norberg et al., 2012; Foden et al., 2013). More studies have scrutinized caveats to previous studies and assessed their role in either under- or overestimating extinction risks (e.g., Beale et al., 2008; Cressey, 2008; Randin et al., 2009; He and Hubbell, 2011; Harte and Kitzes, 2012), including the role of evolution (Norberg et al., 2012), while others have carefully examined risk considering other species traits (looking at exposure, sensitivity, and potential adaptive capacity for large numbers of species; Foden et al., 2013). Literature incorporating multiple new assessment techniques quantifying extinction risks supports the conclusion that the dependence between increasing extinction risk and temperature is *robust* (*medium confidence*), albeit varying across biota. However, there is *low agreement* on assigning specific numerical values for species at risk (Sections 19.3.2.1, 19.5.1). Since AR4 it has been found that not only endemics (which have tended to be the focus of many previous studies) but species geographically widespread are at risk (Warren et al., 2013a), implying a significant and widespread potential loss of ecosystem services (Section 4.3.2.5; Gaston and Fuller, 2008; Allesina et al., 2009; Staudinger et al., 2012), comprising a new emergent risk (Table 19-4). At a global temperature rise of 3.5°C to 4°C above preindustrial, Foden et al. (2013) estimated that 30 to 60% of the birds and amphibians and 40 to 62% of the corals studied are highly vulnerable to climate change. Taking this estimate conservatively as a maximum (i.e., assuming all species not studied are able to adapt at least as well as the groups investigated), and combining this estimate with the finding of ≥50% loss of potential range in 57% of plants and 34% of animals studied globally for a global temperature rise of 3.5°C to 4°C by the 2080s allowing for realistic dispersal rates (Warren et al., 2013a), there is *high confidence* that climate change will significantly affect biodiversity and related ecosystem services.

Much new work has focused on future projected synergistic impacts of climate change-induced increases in fire, drought, disease, and pests (Flannigan et al., 2009; Hegland et al., 2009; Koeller et al., 2009; Krawchuk et al., 2009; Garamszegi, 2011). New work has demonstrated that the expected large turnovers of more than 60% in marine species assemblages by the 2050s in response to climate change (under SRES scenarios A1B and B1), combined with shrinkage of fish body weight of 14 to 24% (SRES A2; Cheung et al., 2009, 2013), put marine ecosystem functioning at risk with negative consequences for fishing industries, coastal communities, and wildlife that are dependent on marine resources (Lam et al., 2012).

Consistent with AR4, global aggregate economic impacts from climate change are highly uncertain, with most estimates a small fraction of gross world product up until at least 2.5°C of warming above preindustrial (Section 10.9.2; Figure 10-1). Some studies suggest net benefits of climate change at 1°C of warming (Section 10.9.2; Figure 10-1). Little is known about global aggregate damages above 3°C (Sections 10.9.2, 19.5.1; Figure 10-1; Ackerman et al., 2010; Weitzman, 2010; Ackerman and Stanton, 2012; Kopp et al., 2012). Aggregate damages vary with alternative development pathways, but the relationship between development pathway and aggregate damages is not well explored. In many sectors, damages as a fraction of output are expected to be larger in low-income economies, although monetized damages are expected to be larger in high-income economies (e.g., Anthoff and Tol, 2010). Adaptation is treated differently across modeling studies (Hope, 2006; de Bruin et al., 2009; Bosello et al., 2010; Füssel, 2010; Patt et al., 2010) and affects aggregate damage estimates in ambiguous ways.

Estimates of global aggregate economic damages omit a number of factors (Yohe and Tirpak, 2008; Kopp and Mignone, 2012). While some studies of aggregate economic damages include market interactions between sectors in a computable general equilibrium framework (e.g., Bosello et al., 2012a; Roson and van der Mensbrugghe, 2012), none treat non-market interactions between impacts (Warren, 2011), such as the effects of the loss of biodiversity among pollinators and wild crops on agriculture or the effects of land conversions owing to shifts in agriculture on terrestrial ecosystems (see Sections 19.3-4). They do not include the effects of the degradation of ecosystem services by climate change (Section 19.3.2.1) and ocean acidification (Section 19.5.2), and in general assume that market services can substitute perfectly for degraded environmental services (Sterner and Persson, 2008; Weitzman, 2010; Kopp et al., 2012). The global aggregate damages associated with large-scale singular events (Section 19.6.3.6) are not well explored (Kopp and Mignone, 2012; Lenton and Ciscar, 2013).

The risk associated with global aggregate impacts is similar to that expressed in AR4 and Smith et al. (2009), as indicated in Figure 19-4, with risk based primarily on economic damages and confidence in the assessment unchanged. For aggregate economic impacts, there is *low* to *medium confidence* in attribution of climate change influence on a few sectors (Section 18.6.4; Table 18-11) so that this RFC is still shaded white at recent temperature in Figure 19-4. Risks of global aggregate impacts are moderate for additional warming between 1°C to 2°C compared to 1986–2005, reflecting impacts to both Earth's biodiversity and the overall global economy (*medium confidence*). Extensive biodiversity loss with associated loss of ecosystem goods and services

results in high risks around 3°C additional warming (*high confidence*). Aggregate economic damages accelerate with increasing temperature (*limited evidence*, *high agreement*) but few quantitative estimates have been completed for additional warming around 3°C or above.

19.6.3.6. Large-Scale Singular Events: Physical, Ecological, and Social System Thresholds and Irreversible Change

Large-scale singular events (sometimes called "tipping points," or critical thresholds) are abrupt and drastic changes in physical, ecological, or social systems in response to smooth variations in driving forces (Smith et al., 2001, 2009; McNeall et al., 2011). Combined with widespread vulnerability and exposure, they pose key risks because of the potential magnitude of the consequences; the rate at which they would occur; and, depending on this rate, the limited ability of society to cope with them. Research on the societal impacts associated with such events is limited; we focus in this section on physical hazards and ecological thresholds.

Regarding singular events in physical systems, AR4 expressed *medium confidence* that at least partial deglaciation of the Greenland ice sheet, and possibly the West Antarctic ice sheet (WAIS), would occur over a period of time ranging from centuries to millennia for a global average temperature increase of 1°C to 4°C (relative to 1990–2000), causing a contribution to sea level rise of 4 to 6 m or more (Schneider et al., 2007). Studies since AR4 are consistent with these judgments but provide a more detailed view (see WGI AR5 Chapter 13). The Greenland ice sheet (*very likely*) and the Antarctic ice sheet (*medium confidence*) contributed to the 5 m higher than present (*very high confidence*) to 10 m above present (*high confidence*) sea level rise that occurred during the Last Interglacial (WGI AR5 SPM; Kopp et al., 2009; McKay et al., 2011; Dutton and Lambeck, 2012). This period provides a partial analog for the magnitude of mid- to late-21st century warming because GMT was not more than 2°C warmer than preindustrial (*medium confidence*; WGI AR5 SPM; Section 5.3.4). However, the resulting sea level rise may have taken millennia to complete.

With regard to projection, WGI AR5 finds that "There is *high confidence* that sustained warming greater than some threshold would lead to the near-complete loss of the Greenland ice sheet over a millennium or more, causing a global mean sea level rise of up to 7 m. Current estimates indicate that the threshold is greater than about 1°C (*low confidence*) but less than about 4°C (*medium confidence*) global mean warming with respect to preindustrial" (WGI AR5 SPM). A threshold for the disintegration of WAIS remains difficult to identify due to shortcomings in various aspects of ice sheet modeling, including representation of the dynamical component of ice loss and ocean processes. For RCP8.5, projected sea level rise is 1 to more than 3 m (*medium confidence*) by 2300. Beyond 2300, "Sustained mass loss by ice sheets would cause larger sea level rise, and some part of the mass loss might be irreversible" (WGI AR5 SPM). Extreme exposure and vulnerability to the *magnitude* of sea level rise associated with loss of a significant fraction of either ice sheet is found worldwide (Nicholls and Tol, 2006) but millennial time scales for ice loss allow greater opportunities to adapt successfully than do century scales, so *timing* is a critical and highly uncertain factor in assessing the risk.

There is also additional evidence regarding singular events in other physical systems. Feedback processes in the Earth system could cause accelerated emissions of CH_4 from wetlands, permafrost, and ocean hydrates. There are large uncertainties in the size of carbon stores, the time scales of release, and the fate of the carbon once released. The probability of substantial carbon release in the form of CH_4 or CO_2 increases with warming (Archer et al., 2009; O'Connor et al., 2010). WGI AR5 finds "*low confidence* in modelling abilities to simulate transient changes in hydrate inventories, but large CH_4 release to the atmosphere during this century is *unlikely*" (WGI AR5 Section 6.4.7.3). Owing to such uncertainties, the existence of a tipping point cannot be ascertained.

AR4 stated that Arctic summer sea ice disappears almost entirely in some projections by the end of the century (WGI AR4 Section 10.3); WGI AR5 finds that a "nearly ice-free Arctic Ocean (sea ice extent less than 1×10^6 km^2 for at least 5 consecutive years) in September before mid-century is *likely* under RCP8.5 (*medium confidence*)." Furthermore, "There is little evidence in global climate models of a tipping point (or critical threshold) in the transition from a perennially ice-covered to a seasonally ice-free Arctic Ocean beyond which further sea ice loss is unstoppable and irreversible" (WGI AR5 Chapter 12 ES). Whether or not the physical process is reversible, effects of ice loss on biodiversity may not be.

Large uncertainties remain in estimating the probability of a shutdown of the AMOC. One expert elicitation finds the chance of a shutdown to be between 0 and 60% for global average warming between 2°C and 4°C, and between 5 and 95% for 4°C to 8°C of warming relative to 2000 (Zickfeld et al., 2007; Kriegler et al., 2009). AR5 judges that "It is *very unlikely* that the AMOC will undergo an abrupt transition or collapse in the 21st century for the scenarios considered. There is *low confidence* in assessing the evolution of the AMOC beyond the 21st century because of the limited number of analyses and equivocal results. However, a collapse beyond the 21st century for large sustained warming cannot be excluded" (WGI AR5 SPM).

Regarding regime shifts in ecosystems, there are "early warning signs" from detection and attribution analysis that both Arctic and warmwater coral reef systems are experiencing irreversible regime shifts (Section 18.6.4). Recent observational evidence confirms the susceptibility of the Amazon to drought and fire (Adams et al., 2009; Phillips et al., 2009), and recent improvements to models provide increased confidence in the existence of a tipping point in the Amazon from humid tropical forest to seasonal forest or grassland as the dominant ecosystem (Jones et al., 2009; Lapola et al., 2009; Malhi et al., 2009; Section 4.3.3.1; Figure 4-8; Box 4-3). In contrast, one recent study suggests that the Amazon may be less susceptible to crossing a tipping point than previously thought (Cox et al., 2013), although this is contingent on the uncertain role of CO_2 fertilization being as strong as models project. Overall, recent "multi-model estimates based on different CMIP3 climate scenarios and different dynamic global vegetation models predict a moderate risk of tropical forest reduction in South America and even lower risk for African and Asian tropical forests" (WGI AR5 Section 12.4.8.2).

Based on the weight of the above evidence, we judge that the overall risk from large-scale singular events is somewhat higher than assessed in AR4 and indicated by Smith et al. (2009). The position of the transition

from white to yellow between 0°C and 1°C compared to 1986–2005 remains as before but with higher confidence due to the existence of early warning signs regarding regime shifts in Arctic and warmwater coral reef systems. The transition from yellow to red occurs over a range from 1°C to more than 3°C, consistent with Smith et al. (2009) and based primarily on the uncertainty in the warming level associated with eventual ice sheet loss. However, we assess a faster increase in risk as temperature increases between 1°C and 2°C compared to 1986–2005, largely determined by the risk arising from a very large sea level rise due to ice sheet loss as occurred during the Last Interglacial when GMT was no more than 2°C warmer than preindustrial (*medium confidence*; WGI AR5 Sections 5.3.4, 5.6.2). This assessment of risk is based primarily on the *magnitude* and *irreversibility* of such sea level rise and the widespread exposure and vulnerability to it. However, as noted, the slower the rate of rise, the more feasible becomes adaptation to reduce vulnerability and exposure. Owing to this uncertainty in *timing*, we refrain from imposing a transition to purple in Figure 19-4.

19.7. Assessment of Response Strategies to Manage Risks

The management of key and newly identified risks of climate change can include mitigation that reduces the likelihood of climate changes and physical impacts and adaptation that reduces the exposure and vulnerability of society and ecosystems to both. Key risks, impacts, and vulnerabilities to which societies and ecosystems may be subject will depend in large part on the mix of mitigation and adaptation measures undertaken, as will the evaluation of RFCs (Section 19.6.3). This section therefore assesses relationships between mitigation, adaptation, and the residual impacts that generate key risks. It also considers limits to both mitigation and adaptation responses, because understanding where these limits lie is critical to anticipating risks that may be unavoidable. Potential impacts involving thresholds for large changes in physical, ecological, and social systems (Section 19.6.3.6) are particularly important elements of key risks, and the section therefore assesses response strategies aimed at avoiding them or adapting to crossing them.

19.7.1. Relationship between Adaptation Efforts, Mitigation Efforts, and Residual Impacts

Under any plausible scenario for mitigation and adaptation, some degree of risk from residual damages is unavoidable (*very high confidence*). Evaluating potential mixes of mitigation, adaptation, and impacts requires joint consideration of outcomes for climate change and socioeconomic development. A principal way in which these different mixes are assessed is comparing the impacts that result from scenarios with little or no mitigation (and therefore more climate change) to those with substantial mitigation (and less climate change). Climate change mitigation costs have been extensively explored (WGIII AR5 Chapter 6), but there has been less work on quantifying the impacts avoided by mitigation and, with the exception of studies of the impacts of sea level rise (Nicholls et al., 2011), treatment of adaptation has been limited and uneven. In this section, unless otherwise stated, global temperature rise is given relative to preindustrial (1850–1900) levels.

Impact studies generally indicate that mitigation can reduce a large proportion of climate change impacts that would otherwise occur (*high confidence*). In one study, mitigation that stabilizes global CO_2 concentrations at 550 ppm reduces by 80 to 95% the number of people additionally at risk of hunger (largely in Africa) in 2080 under an SRES A2 scenario with CO_2 concentrations of 800 ppm, creating an estimated benefit of US$23 to 34 billion of agricultural output compared to the un-mitigated case (Tubiello and Fischer, 2007). In Africa, there are much greater impacts on crop productivity, freshwater resources, and ecosystems at 4°C than at 2°C, with adaptation failing to reduce risk below a "high" level at 4°C ("very high" for crop productivity), whereas at 2°C risks are lower and adaptation could reduce these risks to a "medium" level (Table 22-6). In North America, with 4°C warming, adaptation is not expected to reduce risks below "high" for urban flooding (both riverine and coastal) or for fire damage in ecosystems, or below "medium" for heat-related human mortality. Without adaptation, risk is "very high" for these sectors. In contrast, at 2°C risks are at the "high" level for urban flooding and heat-related human mortality, but the risk of fire in ecosystems is still "very high." At 2°C, adaptation is expected to reduce urban flooding risk to "medium" and heat-related human mortality risk to "low" (Table 26-1). Impacts on water resources would also be reduced (Table 3-2). Fung et al. (2011) and Gosling and Arnell et al. (2013) both found that climate change-induced increases in water stress (defined as persons with <1700 or <1000 m^3 per capita per year respectively in the two studies) globally would be reduced significantly were global temperature rise to be constrained to 2°C rather than 4°C. Reducing climate change from an RCP8.5 scenario to an RCP2.6 scenario reduces the proportion of the global population that experiences >10% declines in available groundwater from 27 to 50% to 11 to 39% (Portmann et al., 2013).

Figure 19-6 highlights results from three studies that estimated the global avoided impacts for multiple sectors when global average temperature is limited to 2°C rather than following scenarios with no mitigation, such as the SRES A1B or A1FI baseline scenarios in which global average temperature reaches 4°C and 5.6°C, respectively (Arnell et al., 2013; Warren et al., 2013a,b). The studies isolate the effects of climate change by using common socioeconomic assumptions in mitigation and baseline scenarios. Overall, sector-specific impacts were reduced by 20 to 80%, with aggregate global economic damages reduced by about one-half (Warren et al., 2013b). The largest impacts avoided were for crop productivity, drought in cropland, biodiversity, exposure to coastal and pluvial flooding, and energy use for cooling, while avoided impacts were smaller for water resources stress. Because some areas become wetter and others drier (WGI AR5 Section 12.4.5), there are regions where climate change results in decreases in flood, drought, or water stress, which may be beneficial. (Note that reduced water stress is not necessarily beneficial; for example, if increased precipitation occurs in a small number of isolated heavy rainfall events, water cannot easily be stored and can cause flooding). This means that as well as avoiding a large amount of negative impacts, mitigation is projected to result in the avoidance of some benefits that are projected to result from climate change, although these avoided benefits are much smaller than the avoided impacts. There are shown as the blue bars in Figure 19-6. Avoided impacts are significantly larger when an A1FI baseline is used compared to an A1B baseline (Figure 19-6) because emissions and global temperature rise are greater in the A1FI baseline

scenario. All of these studies employed an ensemble of climate change projections based on emulation of seven different Global Climate Models (GCMs). The proportion of impacts avoided at the global scale was relatively robust to uncertainties in regional climate projection, but the magnitude of avoided impacts varied considerably with climate projection uncertainty.

The timing of emissions reductions strongly affects impacts. In general fewer impacts can be avoided when mitigation is delayed (Arnell et al., 2013; Warren et al., 2013a,b; Figure 19-6b) because there are limits to how fast emissions can be reduced subsequently to compensate for the delay (Section 19.7.2). For example, if global emissions peak in 2016 and are then reduced at 5% annually, one half of global aggregate economic

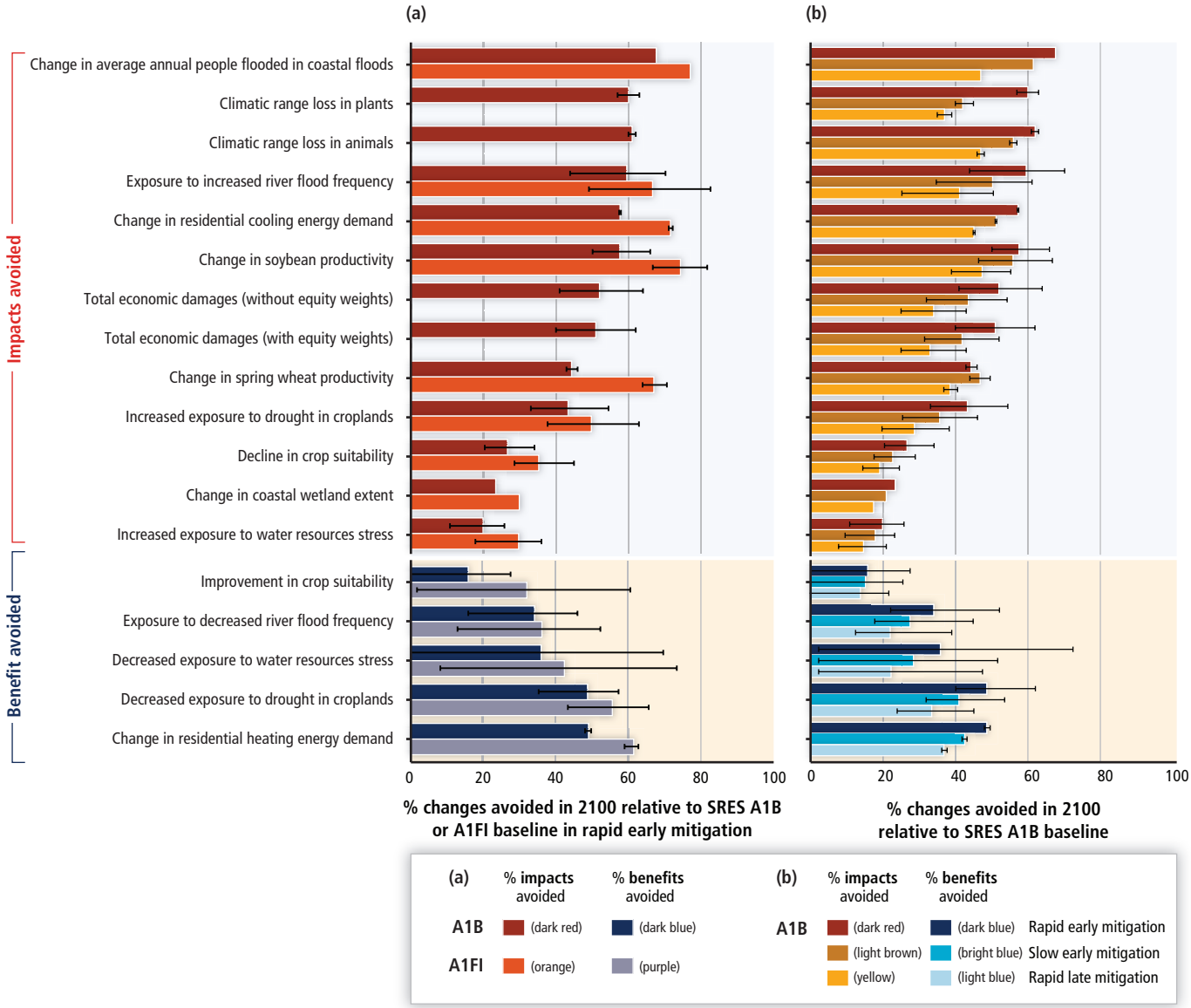


Figure 19-6 | (a) Climate change impacts avoided by an early, rapid mitigation scenario in which global emissions peak in 2016 and are reduced at 5% thereafter, compared to two no-mitigation baseline cases, Special Report on Emission Scenarios (SRES) A1B (dark red bars) and SRES A1FI (orange bars). Impacts avoided are larger if the A1FI baseline scenario is used than if the A1B baseline is used, because greenhouse gas emissions in A1FI exceed those in A1B (see Section 19.7.1). Since the literature does not provide estimates of avoided impacts relative to the A1FI baseline for all sectors considered here, some bars are absent from the panel (a). (b) The dependence of the potential to avoid climate change impacts upon the timing of emission reductions is illustrated. Climate change impacts avoided by the same early, rapid mitigation scenario compared to the no-mitigation baseline case SRES A1B (dark red bars) are shown. The information displayed is identical to the orange bars in (a), but a comparison is now made with the impacts avoided from two other less stringent mitigation scenarios. Impacts avoided if global emissions peak in 2016 but are subsequently reduced more slowly (2% annually) are lower (light brown bars compared to dark red bars). However, if mitigation occurs later, so that global emissions do not peak until 2030, even if emissions are subsequently reduced at 5% annually, the avoided impacts are smaller than in either of the other two cases (yellow bars compared to dark red and light brown bars). Both panels show the uncertainty range (error bars) due to regional climate change projected with seven global climate models. Errors due to uncertainty within impacts models are not shown. Uncertainties associated with sea level rise related impacts are not provided because the models used a single sea level rise projection. Because increases and decreases in water stress, flood risks, and crop suitability are not co-located and affect different regions, these effects are not combined. Since some areas become wetter and others drier (WGI AR5 Section 12.4.5), there are regions where climate change results in decreases in flood, drought, or water stress, which may be beneficial. This means that avoided benefits of climate change, as well as avoided impacts of climate change, are also shown here, as the shorter blue bars. Overall the avoided impacts greatly outweigh the avoided benefits (Arnell et al., 2013; Warren et al., 2013a,b).

impacts might be avoided (Figure 19-6b, orange bars), or around 43% if emissions are reduced more slowly at 2% annually (Figure 19-6b, pink bars); compared to only one-third if emissions peak in 2030 even if emissions are reduced at 5% thereafter (Warren et al., 2013b, Figure 19-6b, brown bars). This applies irrespective of whether or not equity weighting is used in the impact valuation process.

Avoided impacts vary significantly across regions as well as sectors (*high confidence*) due to (1) differing levels of regional climate change, (2) differing numbers of people and levels of resources at risk in different regions, and (3) differing sensitivities and adaptive capacities of humans, species, or ecosystems (Tubiello and Fischer, 2007; Ciscar et al., 2011; Arnell et al., 2013; Section 25.10.1). The length of time it takes for avoided impacts to accrue is determined partly by the nature of the climate system. Benefits accrue least rapidly for impacts associated with sea level rise such as coastal flooding and loss of mangroves and coastal wetlands because sea level rise responds very slowly to mitigation efforts (Meehl et al., 2012). Nevertheless, mitigation may limit 21st century impacts of increased coastal flood damage, dry land loss, and wetland loss substantially (*limited evidence*, *medium agreement*) albeit there is *little agreement* on the exact magnitude of this reduction (Section 5.4.3.1). Benefits accrue more rapidly for impacts associated with global temperature change (WGI AR5 Section 12.5.2, Figure 12.44) and those associated with reduced ocean acidification because surface pH responds relatively quickly to changes in emissions of CO_2 (FAQ 30.1).

In WGIII AR5 Chapter 6, the emission scenarios in the literature (as collected in the AR5 database) have been categorized on the basis of the 2100 radiative forcing (in a total of seven categories). Most Integrated Assessment Models (IAMs) provide information on concentration, forcing, and temperature. However, as the climate components of the IAMs differ, all scenarios were reanalyzed in the simple climate model Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC; Meinshausen et al., 2011) using its probabilistic set-up. The results of this categorization can be used to connect emission trajectories to climate outcomes (Figure 19-7a) and impacts and risks (Figure 19-7b; Table 19-4).

Mitigation scenarios in category 1 with a 2100 CO_2-eq concentration of 430 to 480 ppm result in a median projected 2100 global temperature rise of between 1.5°C and 1.7°C above preindustrial (10–90% range 1.0–2.8°C) (Figure 19-7a; WGIII AR5 Table 6.3). These scenarios correspond to a 2011–2100 cumulative emission level of around 630–1180 $GtCO_2$ (WGIII AR5 Table 6.3). Under these scenarios, based on the MAGICC calculations, warming is *likely* to stay below 2°C and *very likely* to stay below 3°C during the 21st century. This significantly reduces the key risks listed in Table 19-4, as well as others discussed in this chapter. Constraining global temperature rise to 2°C would constrain the risks associated with global aggregate impacts and large-scale singular events to the yellow or moderate level and the risks associated with the distribution of impacts, extreme weather events, and to unique and threatened systems to the lower part of the red or high level. If global

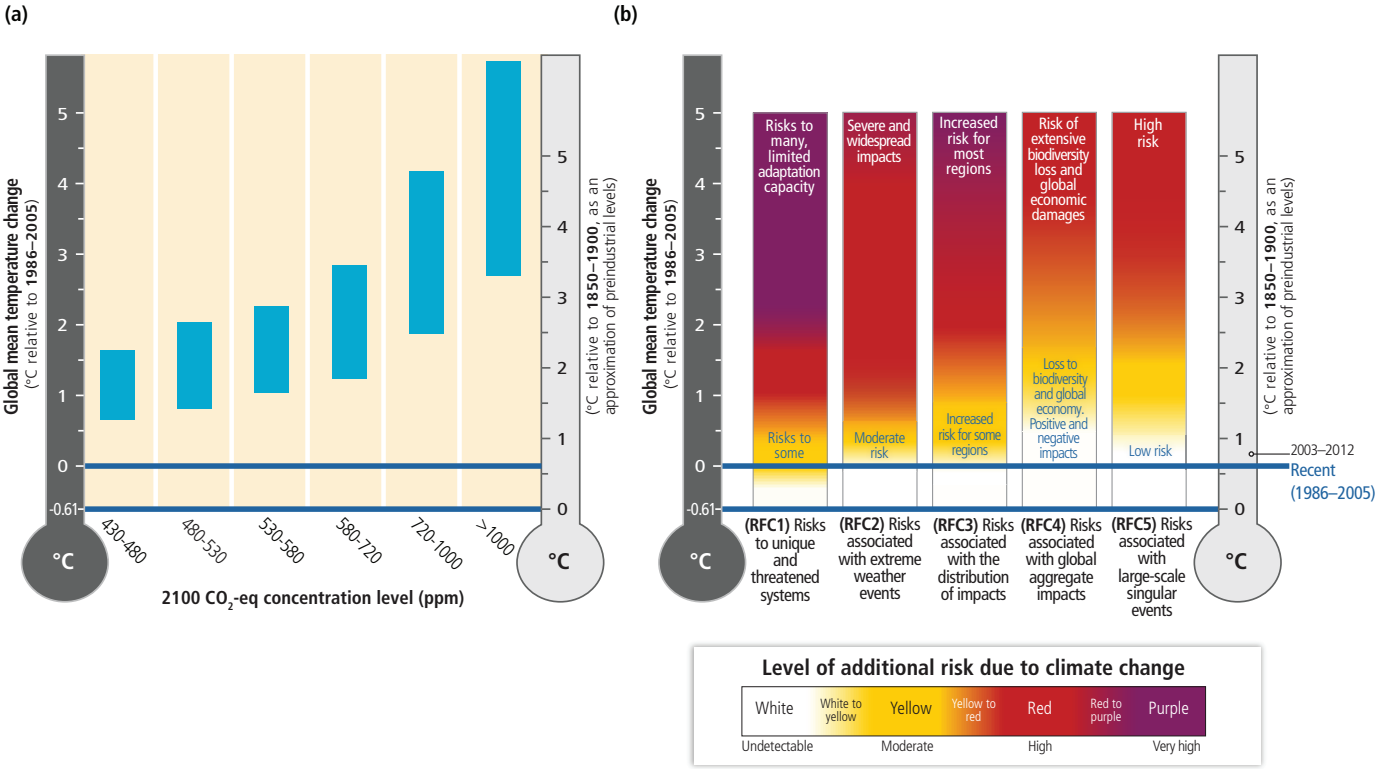


Figure 19-7 | Relationship between mitigation scenario categories considered in WGIII AR5, in terms of their CO_2-eq concentrations and global temperature rise outcomes in 2100, and level of risk associated with Reasons for Concern. (a) The projected increase in global mean temperature in 2100 compared to pre-industrial and recent (1986–2005), calculated using the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) climate model for the scenario categories defined in WGIII AR5 Chapter 6, indicating the uncertainty range resulting both from the range of emission scenario projections within each category (10–90th percentile) and the uncertainty in the climate system as represented by MAGICC (16–84th percentile) (data taken from WGIII AR5 Chapter 6). (b) Reproduction of Figure 19-4 for ease of comparison. Beyond 2100, temperature, and therefore risk, decreases in most of the lowest three scenarios and increases further in most of the others.

temperature rise were 1.5–1.7°C only, risks to unique and threatened systems and risks associated with extreme weather events would be further constrained to the transition between moderate and high risk levels. The temperature levels in the RCP2.6 scenario are 1.2°C to 2.0°C (WGI AR5 Table 12.2) matching closely the scenarios in this category.

Mitigation scenarios in category 2 with a concentration of 480 to 530 ppm CO_2-eq in 2100 correspond to a median projected 2100 global temperature rise of between 1.7°C and 2.1°C (10–90% range 1.2–3.3°C) in the MAGICC calculations. These scenarios correspond to a cumulative emission level over the 2011–2100 period on the order of 960–1550 $GtCO_2$ (WGIII AR5 Table 6.3) and are *as likely as not* to stay below 2°C, but are still *very unlikely* to rise above 3°C. Thus, scenarios in category 2 also reduce risks, but to a lesser extent than for category 1. If global temperature rise reaches 2.5°C in 2100, levels of risk due to extreme weather events are at the red or high level, while those to unique and threatened systems now reach the very high or purple level reflecting inability to adapt. Risks associated with global aggregate impacts reach the transition zone from yellow or moderate level to red or high risk, while risks associated with the distribution of impacts and large-scale singular events reach the red or high level.

Mitigation scenarios in category 3 with 530 to 580 ppm CO_2-eq in 2100 correspond to a median projected temperature rise of between 2.0°C and 2.3°C (range 1.4–3.6°C) above preindustrial levels (WGIII AR5 Table 6.3) such that it is *very unlikely* that temperature rise would stay below 1.5°C, and less probable than category 2 to remain below 2°C, affording little protection to coral reefs. In this category, risks to unique and threatened systems remain high or very high indicating inability to adapt. Risks associated with extreme weather events remain at the high level. Risks associated with the distribution of impacts, global aggregate impacts and large-scale singular events range from moderate to high.

Mitigation scenarios in category 4 with 580 to 720 ppm CO_2-eq in 2100 result in a range of possible temperature outcomes between 2.3°C and 2.9°C (10–90% range 1.5–4.5°C) above preindustrial levels, affording no protection to coral reefs. In these scenarios, it is *more likely than not* that global temperature rise would exceed 2°C (WGIII AR5 Table 6.3) so that risks to unique and threatened systems remain high or very high indicating inability to adapt. Risks associated with extreme weather events and the distribution of impacts are high. Levels of risk associated with global aggregate impacts and large-scale singular events may be moderate or high (*high confidence*). Global temperature rise in RCP4.5 in 2100 is 1.9 to 2.9°C above preindustrial levels (WGI AR5 Table 12.2), matching the low scenarios in this category.

Onset of large-scale dissolution of coral reefs is projected if CO_2 concentrations reach 560 ppm (Sections 5.4.1.6, 5.4.2.4, 19.6.3.2, 26.4.3.2; Silverman, 2009), due to the combined effects of warming and ocean acidification. However, already at 450 ppm, reef growth rates are projected to be reduced by more than 60% globally and by at least 20% globally at 380 ppm (Silverman, 2009). Coral organisms themselves are projected to be damaged by warming at concentrations below 560 ppm: specifically, even with optimistic assumptions regarding the ability of corals to rapidly adapt to thermal stress, RCP4.5 is projected to result in long-term degradation of two-thirds of coral reefs, compared with one-third of them under RCP3PD (Box CC-CR). Hence, maintenance of moderately healthy coral reefs is consistent only with scenarios in the scenarios in the 430 to 480 ppm CO_2-eq category; while some reef protection is achieved with scenarios in the category 480 to 530 ppm CO_2-eq. A low level of protection exists for the category 530 to 580 ppm CO_2-eq while all other categories exceed the 560 ppm level.

Finally, scenarios in category 6 with a concentration level of >1000 ppm CO_2-eq are projected to result in median 2100 temperature rise of 4.1°C to 4.8°C (range 2.8–7.8°C) above preindustrial with negligible chances to constrain it below 2°C above preindustrial (Figure 19-7a) and would allow significant key risks to persist in all the areas listed in Table 19-4. Risk is at the red level for all RFCs except unique and threatened systems, where risk is at the purple level indicating infeasibility of adaptation. For the distribution of impacts, risk reaches the transition to purple if temperatures rise in excess of 4°C above preindustrial levels. For the scenarios with a concentration level between 720 ppm and 1000 ppm (category 5) outcomes for risk levels are high or very high, except that risk of global aggregate impacts ranges from the transition zone from moderate risk up to high risk.

Scenarios with rapid, early mitigation (particularly those with a 2100 CO_2-eq concentration of 430 to 480 ppm) generally delay the onset of a given global annual mean temperature rise until several decades later in the century than is the case for scenarios with slower, delayed mitigation or no mitigation (such as those with a 2100 CO_2-eq concentration of 720 to 1000 ppm), thus allowing impacts to be further reduced by adaptation during this time.

19.7.2. Limits to Mitigation

Mitigation possibilities, such as those implicit in scenarios discussed in Section 19.7.1, are not unlimited. Assessment of maximum feasible mitigation (and lowest feasible emissions pathways) must account for the fact that feasibility is a subjective concept encompassing technological, economic, political, and social dimensions (Hare et al., 2010). Most mitigation studies have focused on technical feasibility, for example, demonstrating that it is possible to reduce emissions enough to have at least a 50% chance of limiting warming to less than 2°C relative to preindustrial (den Elzen and van Vuuren, 2007; Clarke et al., 2009; Edenhofer et al., 2010; Hare et al., 2010; O'Neill et al., 2010), taking into account uncertainty in climate and carbon cycle response to emissions (see WGI AR5 Section 12.5.4 for a discussion of uncertainties in the relationship between emissions and long-term climate stabilization targets). RCP2.6, based on an integrated assessment model-based mitigation scenario (van Vuuren et al., 2012), is *unlikely* to produce more than 2°C of warming relative to preindustrial (*medium confidence*; WGI AR5 Section 12.4.1.1). Such scenarios lead to pathways in which global emissions peak within the next 1 to 2 decades and decline to 50 to 85% below 2000 levels by 2050 (or 40 to 70% compared to 1990 levels), and in some cases exhibit negative emissions before the end of the century (den Elzen et al., 2007, 2010; IPCC, 2007b; van Vuuren et al. 2012). Very few integrated assessment model-based scenarios in the literature demonstrate the feasibility of limiting warming to a maximum of 1.5°C with at least 50% likelihood (Rogelj et al., 2012); most 1.5°C scenarios have been based on stylized emissions pathways (Hare et al.., 2010;

Ranger et al., 2012). The highest emission reduction rate considered in most integrated modeling studies that attempt to minimize mitigation cost is typically between 3 and 4% but with larger values not ruled out although some studies find that for an additional cost higher rates may be achievable (den Elzen et al., 2010; O'Neill et al., 2010).

However, most studies of feasibility include a number of idealized assumptions, including availability of a wide range of mitigation technologies such as carbon capture and storage (CCS) and large-scale renewable and biomass energy. Most also assume universal participation in mitigation efforts beginning immediately, economically optimal reductions (i.e., reductions are made wherever they are cheapest), and no constraints on policy implementation. Any deviation from these idealized assumptions can significantly limit feasible mitigation reductions (Knopf et al., 2010; Rogelj et al., 2012). For example, delayed participation in reductions by non-Organisation for Economic Co-operation and Development (OECD) countries made concentration limits such as not exceeding 450 ppm CO_2-eq (roughly consistent with a 50% chance of remaining below 2°C relative to preindustrial), and in some cases even 550 ppm CO_2-eq, unachievable in some models unless temporary overshoot of these targets (Izrael and Semenov, 2006) were allowed (Clarke et al., 2009), but not in others (Waldhoff and Fawcett, 2011). Technology limits, such as unavailability of CCS or limited expansion of renewables or biomass, makes stabilization at 450 ppm CO_2-eq (or 2°C with a 50% chance) unachievable in some models (Krey and Riahi, 2009; van Vliet et al., 2012). Similarly, if the political will to implement coordinated mitigation policies within or across a large number of countries were limited, peak emissions and subsequent reductions would be delayed (Webster, 2008).

These considerations have led some analysts to doubt the plausibility of limiting warming to 2°C (Anderson and Bows, 2008, 2011; Tol, 2009). "Emergency mitigation" options have also been considered that would go beyond the measures considered in most mitigation analyses (Swart and Marinova, 2010). These include drastic emissions reductions achieved through limits on energy consumption (Anderson and Bows, 2011) or geoengineering through management of the Earth's radiation budget (Section 19.5.4; WGI AR5 Chapters 6, 7).

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19.7.3. Avoiding Thresholds, Irreversible Change, and Large-Scale Singularities in the Earth System

Section 19.6.3.6 discussed the RFC related to nonlinear changes in the Earth system ("large-scale singular events"), whereby anthropogenic forcings might cause irreversible and potentially rapid transitions over a wide range of time scales (see Section 19.6.3; WGI AR5 SPM, TS, TFE.5, Section 12.5; Lenton et al., 2008). The risk of triggering such transitions generally increases with increasing anthropogenic climate forcings/climate change (Lenton et al., 2008; Kriegler et al., 2009; Levermann et al., 2012). Reducing GHG emissions is projected to reduce the risks of triggering such transitions (*medium confidence*). Adaptation could reduce their potential consequences, but the efficacy of adaptation might be limited, for example for rapid transitions (Section 19.7.5).

Several studies have sought to identify levels of atmospheric GHG concentrations or global average temperature change that would limit the risks of triggering these transitions (e.g., Keller et al., 2005, 2008; Lenton et al., 2008; Kriegler et al., 2009). Section 19.6.3.6 assesses evidence regarding the relationship between global average temperature and risks of disintegration of major ice sheets, loss of Arctic sea ice, shutdown of the AMOC, carbon releases from temperature-related feedback processes, and regime shifts in ecosystems. Additional aspects of these risks are important to mitigation strategies. For example, it is important to distinguish between triggering and experiencing a threshold response because model simulations suggest that there can be sizable delays between the two (e.g., Lenton et al., 2008). The location of these trigger points can be difficult to determine from process-based models alone, as some of these models lack potentially important processes (see e.g., WGI AR5 Chapter 13).

In this situation, expert elicitations can provide additional useful information for risk assessments. One such assessment based on expert elicitation (Lenton et al., 2008) finds that limiting global mean temperature increase to approximately 3°C above recent (1980–1999) values would considerably reduce the risks of triggering some nonlinear responses. In general, there is *low confidence* in the location of such temperature limits owing to disagreements among experts. Estimates of such temperature limits can change over time (Oppenheimer et al., 2008) and may be subject to overconfidence that can introduce a downward bias in risk estimates of low-probability events (Morgan and Henrion, 1990). The climate threshold responses can interact (e.g., Kriegler et al., 2009). Other climate change metrics (e.g., rates of changes or atmospheric CO_2 concentrations) can also be important in the consideration of response strategies aimed at reducing the risk of crossing thresholds (McAlpine et al., 2010; Lenton, 2011a).

Several analyses have performed risk- and decision-analyses for specific thresholds, mostly focusing on a persistent weakening or collapse of the AMOC (Zickfeld and Bruckner, 2008; Urban and Keller, 2010; Bahn et al., 2011; McInerney et al., 2012). Experiencing AMOC collapse has been assessed as *very unlikely* in this century and there is *low confidence* in assessing the AMOC beyond the 21st century (WGI AR5 SPM). However, owing to lags in the ocean system, the probability of triggering an eventual collapse differs from that of experiencing such an outcome (Urban and Keller, 2010). A probabilistic analysis sampling a subset of the relevant uncertainties concluded that reducing the probability of a collapse within the next few centuries to one in ten requires emissions reductions of roughly 60% relative to a business-as-usual strategy by 2050 (McInerney and Keller, 2008). Bruckner and Zickfeld (2009) show that, under their worst-case assumptions about key parameter values, emissions mitigation would need to begin within the next 2 decades to avoid reducing the overturning rate by more than 50%.

Threshold risk estimates and evaluations of risk-management strategies are sensitive to factors such as the representation of uncertainties and the decision-making frameworks used (Polasky et al., 2011; McInerney et al., 2012). Several analyses have examined how the consideration of threshold events affects response strategies. For example, the design of risk-management strategies could be informed by observation and projection systems that would provide an actionable early warning signal of an approaching threshold response. Learning about key uncertain parameters (e.g., climate sensitivity or impacts of a threshold response) can considerably affect risk-management strategies and have

a sizable economic value of information (Keller et al., 2004; Lorenz et al., 2012). However, there is limited evidence about the feasibility and requirements for such systems owing to the small number of studies and their focus on highly simplified situations (Keller and McInerney, 2008; Lenton, 2011b; Lorenz et al., 2012). In some decision-analytic frameworks, knowing that a threshold has been crossed can lead to reductions in emissions mitigation and a shift of resources toward adaptation and/or geoengineering (Keller et al., 2004; Guillerminet and Tol, 2008; Swart and Marinova, 2010; Lenton, 2011b).

19.7.4. Avoiding Tipping Points in Social/Ecological Systems

Tipping points (see Glossary) in socio-ecological systems are defined as thresholds beyond which impacts increase nonlinearly to the detriment of both human and natural systems. These can be initiated rapidly, inducing a need for rapid response. For example, regime shifts have already occurred in marine food webs (Byrnes et al., 2007; Green et al., 2008; Alheit, 2009; Section 6.3.6) due to (observed) changes in sea surface temperature, changes in salinity, natural climate variability, and/or overfishing.

Because human and ecological systems are linked by the services that ecosystems provide to society (McLeod and Leslie, 2009; Lubchenco and Petes, 2010), tipping points may be crossed when either the ecosystem services are disrupted and/or social/economic networks are disrupted (Renaud et al., 2010). Climate change provides a stress that increases the risk that tipping points will be crossed, although they may be crossed due to other types of stresses even in the absence of climate change. For example, in dryland ecosystems, overgrazing has caused grassland-to-desert transitions (Pimm, 2009).

The likelihood of crossing tipping points due to climate change may be reduced by preserving ecosystem services through (1) limiting the level and rate of climate change (*medium confidence*) and/or (2) removing concomitant stresses such as overgrazing, fishing, habitat destruction, and pollution. Most literature currently focuses on strategy (2), and there is limited information about the exact levels and rates of climate change that specific coupled socioeconomic systems can withstand. Examples of strategy (2) include maintaining resilience of coral reefs and cephalopod or piscivorous seabird populations by removal of concomitant stress from fishing (Andre et al., 2010; Anthony et al., 2011; see also Sections 6.3.6, 30.6.2) or expanding protected area networks (Brodie et al., 2012). Removal of concomitant stress such as nutrient loading can reduce the chance of a regime shift (Jurgensone et al., 2011) in coral reef ecosystems (De'ath et al., 2012). Sometimes management can reverse the crossing of a tipping point, for example, by adding sediment to a submerged salt marsh (Stagg and Mendelssohn, 2010). Strategy (2) is enhanced by resilience-based management approaches in ecosystems (Walker and Salt, 2006; Lubchenco and Petes, 2010; Allen et al., 2011; Selig et al., 2012). A high level of biodiversity increases ecosystem resilience and can enable recovery after crossing a tipping point (Brierley and Kingsford, 2009; Lubchenco and Petes, 2010). Strategy (2) generally becomes ineffective once climate changes beyond an uncertain and spatially variable threshold; also successive thresholds may be crossed as stress increases (Renaud et al., 2010).

Monitoring that aims to detect a slowdown in the recovery of systems from small changes (van Nes and Scheffer, 2005) or to measure an appropriate indicator (Biggs et al., 2008) may give warning that a system is a approaching a regime shift, justifying intervention of type (2) (Guttal and Jayaprakash, 2009; Brock and Carpenter, 2010). Such indicators have been identified for the desertification process in the Mediterranean (Kéfi et al., 2007) and for landscape fire dynamics (Zinck et al., 2011; McKenzie and Kennedy, 2012).

19.7.5. Limits to Adaptation

Sections 16.2 and 16.4 provide a thorough assessment of the literature on limits to adaptation. Discussions are beginning on the nature of such limits, for example, in terms of different dimensions of the limits to adaptation, including financial or economic limits to adapt, but also social and political or cognitive limits of adaptation. Limits to adaptation (see, e.g., Adger et al., 2009) are also recognized in terms of specific geographies, for example, SIDS and their limited ability to adapt to increasing impacts of sea level rise, the limits to adaptation of urban agglomerations and urban dwellers in low-lying coastal zones (see, e.g., Birkmann et al., 2010), or in relation to loss of water supplies as a result of glacier retreat (Orlove, 2009). Overall, the concept of limits to adaptation is closely related to key vulnerabilities and key risks including those identified in Table 19-4 and Box CC-KR, because this concept helps define residual risk.

References

Abbott, P. and A. Borot de Battisti, 2011: Recent global food price shocks: causes, consequences and lessons for African governments and donors. *Journal of African Economies*, **20(Suppl. 1)**, i12-i62.

Abrol, D.P., 2012: Decline in pollinators. In: *Pollination Biology: Biodiversity Conservation and Agricultural Production* [Abrol, D.P. (ed.)]. Springer Science, Dordrecht, Netherlands, pp. 545-601.

Ackerman, F. and J. Fisher, 2013: Is there a water-energy nexus in electricity generation? Long-term scenarios for the western United States. *Energy Policy*, **59**, 235-241.

Ackerman, F. and E.A. Stanton, 2012: Climate risks and carbon prices: revising the social cost of carbon. *Economics: The Open-Access, Open Assessment E-Journal*, **6**, 2012-10, doi:10.5018/economics-ejournal.ja.2012-10.

Ackerman, F., E.A. Stanton, and R. Bueno, 2010: Fat tails, exponents, extreme uncertainty: simulating catastrophe in DICE. *Ecological Economics*, **69(8)**, 1657-1665.

Adam, C. and O. Ajakaiye, 2011: Causes, consequences and policy implications of global food price shocks: introduction and overview. *Journal of African Economies*, **20(Suppl. 1)**, i3-i11.

Adams, H.D., M. Guardiola-Claramonte, G.A. Barron-Gafford, J.C. Villegas, D.D. Breshears, C.B. Zou, P.A. Troch, and T.E. Huxman, 2009: Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global-change-type drought. *Proceedings of the National Academy of Sciences of the United States of America*, **106(17)**, 7063-7066.

Adger, W.N., 2006: Vulnerability. *Global Environmental Change*, **16(3)**, 268-281.

Adger, W.N., N.W. Arnell, and E.L. Tompkins, 2005: Successful adaptation to climate change across scales. *Global Environmental Change*, **15(2)**, 77-86.

Adger, W.N., S. Dessai, M. Goulden, M. Hulme, I. Lorenzoni, D. Nelson, L. Naess, J. Wolf, and A. Wreford, 2009: Are there social limits to adaptation to climate change? *Climatic Change*, **93(3)**, 335-354.

Ahmed, S.A., N.S. Diffenbaugh, and T.W. Hertel, 2009: Climate volatility deepens poverty vulnerability in developing countries. *Environmental Research Letters*, **4(3)**, 034004, doi:10.1088/1748-9326/4/3/034004.

Ahrens, J. and P.M. Rudolph, 2006: The importance of governance in risk reduction and disaster management. *Journal of Contingencies and Crisis Management*, **14(4)**, 207-220.

Alheit, J., 2009: Consequences of regime shifts for marine food webs. *International Journal of Earth Sciences*, **98(2)**, 261-268.

Allen, C.R., G.S. Cumming, A.S. Garmestani, P.D. Taylor, and B.H. Walker, 2011: Managing for resilience. *Wildlife Biology*, **17**, 337-349.

Allesina, S., A. Bodini, and M. Pascual, 2009: Functional links and robustness in food webs. *Philosophical Transactions of the Royal Society B*, **364(1524)**, 1701-1709.

Amstrup, S.C., E.T. DeWeaver, D.C. Douglas, B.G. Marcot, G.M. Durner, C.M. Bitz, and D.A. Bailey, 2010: Greenhouse gas mitigation can reduce sea-ice loss and increase polar bear persistence. *Nature*, **468(7326)**, 955-958.

Anderson, K. and A. Bows, 2008: Reframing the climate change challenge in light of post-2000 emission trends. *Philosophical Transactions of the Royal Society A*, **366(1882)**, 3863-3882.

Anderson, K. and A. Bows, 2011: Beyond 'dangerous' climate change: emission scenarios for a new world. *Philosophical Transactions of the Royal Society A*, **369(1934)**, 20-44.

Anderson-Teixeira, K.J. and E.H. DeLucia, 2011: The greenhouse gas value of ecosystems. *Global Change Biology*, **17(1)**, 425-438.

Andre, J., M. Haddon, and G.T. Pecl, 2010: Modelling climate-change-induced nonlinear thresholds in cephalopod population dynamics. *Global Change Biology*, **16(10)**, 2866-2875.

Anthoff, D. and R.S.J. Tol, 2010: On international equity weights and national decision making on climate change. *Journal of Environmental Economics and Management*, **60(1)**, 14-20.

Anthoff, D., R. Nicholls, and R.S.J. Tol, 2010: The economic impact of substantial sea-level rise. *Mitigation and Adaptation Strategies for Global Change*, **15(4)**, 321-335.

Anthony, K., J.A. Maynard, G. Diaz-Pulido, P.J. Mumby, P.A. Marshall, L. Cao, and O. Hoegh-Guldberg, 2011: Ocean acidification and warming will lower coral reef resilience. *Global Change Biology*, **17(5)**, 1798-1808.

Aragón, P. and J.M. Lobo, 2012: Predicted effect of climate change on the invasibility and distribution of the Western corn root-worm. *Agricultural and Forest Entomology*, **14(1)**, 13-18.

Archer, D., M. Eby, V. Brovkin, A. Ridgwell, L. Cao, U. Mikolajewicz, K. Caldeira, K. Matsumoto, G. Munhoven, and A. Montenegro, 2009: Atmospheric lifetime of fossil fuel carbon dioxide. *Annual Review of Earth and Planetary Sciences*, **37**, 117-134.

Arnell, N.W., 2011: Uncertainty in the relationship between climate forcing and hydrological response in UK catchments. *Hydrology and Earth System Sciences*, **15**, 897-912.

Arnell, N.W., J. Lowe, S. Brown, S. Gosling, P. Gottschalk, J. Hinkel, B. Lloyd-Hughes, R. Nicholls, T. Osborn, and T.M. Osborne, 2013: A global assessment of the effects of climate policy on the impacts of climate change. *Nature Climate Change*, **3**, 512-519.

Atzl, A. and S. Keller, 2013: A systemic approach for the analysis of infrastructure-specific social vulnerability. In: *From Social Vulnerability to Resilience: Measuring Progress towards Disaster Risk Reduction* [Cutter, S.L. and C. Corendea (eds.)]. SOURCE No. 17, United Nations University Institute for Environment and Human Security (UNU-EHS), Bonn, Germany, pp. 27-43.

Bahn, O., N.R. Edwards, R. Knutti, and T.F. Stocker, 2011: Energy policies avoiding a tipping point in the climate system. *Energy Policy*, **39(1)**, 334-348.

Bala, G., P.B. Duffy, and K.E. Taylor, 2008: Impact of geoengineering schemes on the global hydrological cycle. *Proceedings of the National Academy of Sciences of the United States of America*, **105(22)**, 7664-7669.

Bálint, M., S. Domisch, C. Engelhardt, P. Haase, S. Lehrian, J. Sauer, K. Theissinger, S. Pauls, and C. Nowak, 2011: Cryptic biodiversity loss linked to global climate change. *Nature Climate Change*, **1(6)**, 313-318.

Balmford, A., J. Kroshko, N. Leader-Williams, and G. Mason, 2011: Zoos and captive breeding. *Science*, **332(6034)**, 1149-1150.

Barnett, J. and W.N. Adger, 2007: Climate change, human security and violent conflict. *Political Geography*, **26(6)**, 639-655.

Barney, J.N. and J.M. Ditomaso, 2008: Nonnative species and bioenergy: are we cultivating the next invader? *BioScience*, **58(1)**, 64-70.

Barnosky, A.D., E.A. Hadly, J. Bascompte, E.L. Berlow, J.H. Brown, M. Fortelius, W.M. Getz, J. Harte, A. Hastings, and P.A. Marquet, 2012: Approaching a state shift in Earth's biosphere. *Nature*, **486(7401)**, 52-58.

Barr K.J., B.A. Babcock, M.A. Carriquiry, A.M. Nassar, L. Harfuch, 2011: Agricultural Land Elasticities in the United States and Brazil. *Applied Economic Perspectives and Policy*, **33 (3)**, 449-462.

Bartlett, S., 2008: Climate change and urban children: impacts and implications for adaptation in low- and middle-income countries. *Environment and Urbanization*, **20(2)**, 501-519.

Beale, C.M., J.J. Lennon, and A. Gimona, 2008: Opening the climate envelope reveals no macroscale associations with climate in European birds. *Proceedings of the National Academy of Sciences of the United States of America*, **105(39)**, 14908-14912.

Beaumont, L.J., A. Pitman, S. Perkins, N.E. Zimmermann, N.G. Yoccoz, and W. Thuiller, 2011: Impacts of climate change on the world's most exceptional ecoregions. *Proceedings of the National Academy of Sciences of the United States of America*, **108(6)**, 2306-2311.

Beck, M.W., B. Gilmer, Z. Ferdaña, G.T. Raber, C.C. Shepard, I. Meliane, J.D. Stone, A.W. Whelchel, M. Hoover, and S. Newkirk, 2013: Increasing the resilience of human and natural communities to coastal hazards: supporting decisions in New York and Connecticut. In: *The Role of Ecosystems in Disaster Risk Reduction* [Renaud, F.G., K. Sudmeier-Rieux, and M. Estrella (eds.)]. United Nations University Press, Tokyo, Japan, pp. 140-163.

Bedford, F.E., R.J. Whittaker, and J.T. Kerr, 2012: Systemic range shift lags among a pollinator species assemblage following rapid climate change. *Botany*, **90(7)**, 587-597.

Bellard, C., C. Bertelsmeier, P. Leadley, W. Thuiller, and F. Courchamp, 2012: Impacts of climate change on the future of biodiversity. *Ecology Letters*, **15(4)**, 365-377.

Benayas, J.M.R., A.C. Newton, A. Diaz, and J.M. Bullock, 2009: Enhancement of biodiversity and ecosystem services by ecological restoration: a meta-analysis. *Science*, **325(5944)**, 1121-1124.

Bernauer, T., T. Böhmelt, and V. Koubi, 2012: Environmental changes and violent conflict. *Environmental Research Letters*, **7(1)**, 015601, doi:10.1088/1748-9326/7/1/015601.

Berry, P., M. Rounsevell, P. Harrison, and E. Audsley, 2006: Assessing the vulnerability of agricultural land use and species to climate change and the role of policy in facilitating adaptation. *Environmental Science & Policy*, **9(2)**, 189-204.

Betts, R. A., N.W. Arnell, P. Boorman, S.E. Cornell, J.I. House, N.R. Kaye, M.P. McCarthy, D. McNeall, M.G. Sanderson, and A.J. Wiltshire, 2012: Climate change impacts and adaptation: an Earth system view. In: *Understanding the Earth System: Global Change Science for Application* [Cornell, S.E., I.C. Prentice, J.I. House, and C. J. Downy (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 160-201.

Biggs, R., H. Simons, M. Bakkenes, R.J. Scholes, B. Eickhout, D. van Vuuren, and R. Alkemade, 2008: Scenarios of biodiversity loss in southern Africa in the 21st century. *Global Environmental Change*, **18(2)**, 296-309.

Birkmann, J., 2006a: *Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies.* United Nations University Press, Tokyo, Japan, 524 pp.

Birkmann, J., 2006b: Measuring vulnerability to promote disaster-resilient societies: Conceptual frameworks and definitions. In: *Measuring Vulnerability to Natural Hazards. Towards Disaster Resilient Societies* [Birkmann, J. (ed.)]. United Nations University Press, Tokyo, Japan, pp. 9-54.

Birkmann, J., 2011: First- and second-order adaptation to natural hazards and extreme events in the context of climate change. *Natural Hazards*, **58(2)**, 811-840.

Birkmann, J. (ed.), 2013: *Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies*. 2nd edn., United Nations University Press, Tokyo, Japan, 686 pp.

Birkmann, J. and N. Fernando, 2008: Measuring revealed and emergent vulnerabilities of coastal communities to tsunami in Sri Lanka. *Disasters*, **32(1)**, 82-105.

Birkmann, J., M. Garschagen, F. Kraas, and N. Quang, 2010: Adaptive urban governance: new challenges for the second generation of urban adaptation strategies to climate change. *Sustainability Science*, **5(2)**, 185-206.

Birkmann, J., D.C. Seng, and D. Suarez, 2011a: *Adaptive Disaster Risk Reduction Enhancing Methods and Tools of Disaster Risk Reduction in the Light of Climate Change* [German Committee for Disaster Reduction (ed.)]. DKKV Publication Series 43, German Committee for Disaster Reduction (DKKV), Bonn, Germany, 51 pp.

Birkmann, J., T. Welle, D. Krause, J. Wolfertz, D.-C. Suarez, and N.Setiadi, 2011b: Governance and civil society. In: *WorldRiskReport 2011* [Bündnis Entwicklung Hilft (ed.)]. Bündnis Entwicklung Hilft (Alliance Development Works) in cooperation with the United Nations University Institute for Environment and Human Security (UNU-EHS) that prepared the WorldRiskIndex, Bündnis Entwicklung Hilft, Berlin, Germany, pp. 13-42.

Birkmann, J., O. Cardona, M. Carreño, A. Barbat, M. Pelling, S. Schneiderbauer, S. Kienberger, M. Keiler, D. Alexander, and P. Zeil, 2013a: Framing vulnerability, risk and societal responses: the MOVE framework. *Natural Hazards*, **67(2)**, 193-211.

Birkmann, J., S.L Cutter, D.S. Rothman, T. Welle, M. Garschagen, B. van Ruijven, B.C. O'Neill, B.L. Preston, S. Kienberger, O.D. Cardona, T. Siagian, D. Hidayati, N. Setiadi, C.R. Binder, B. Hughes, and R. Pulwarty, 2013b: Scenarios for vulnerability: opportunities and constraints in the context of climate change and disaster risk. *Climatic Change*, published online 9 November 2013, doi:10.1007/s10584-013-0913-2.

Black, R.E., L.H. Allen, Z.A. Bhutta, L.E. Caulfield, M. De Onis, M. Ezzati, C. Mathers, and J. Rivera, 2008: Maternal and child undernutrition: global and regional exposures and health consequences. *The Lancet*, **371(9608)**, 243-260.

Blaikie, P., T. Cannon, I. Davis, and B. Wisner, 1994: *At Risk: Natural Hazards, People's Vulnerability, and Disasters.* Routledge, Abingdon, UK and New York, NY, USA, 284 pp.

Blaikie, P., T. Cannon, I. David, and B. Wisner, 1996: *Vulnerabilidad: El Entorno Social, Político y Económico de los Desastres.* LA RED: Red de Estudios Sociales en Prevención de Desastres en América Latina Desastres, Tercer Mundo Editores, Bogotá, Colombia, 374 pp.

Bohle, H.-G., 2001: Vulnerability and criticality: perspectives from social geography. *IHDP Update 2/2001*, *Newsletter of the International Human Dimensions Programme on Global Environmental Change*, 1-7.

Bohle, H.-G., T.E. Downing, and M.J. Watts, 1994: Climate change and social vulnerability: toward a sociology and geography of food insecurity. *Global Environmental Change*, **4(1)**, 37-48.

Bolch, T., A. Kulkarni, A. Kääb, C. Huggel, F. Paul, J. Cogley, H. Frey, J. Kargel, K. Fujita, and M. Scheel, 2012: The state and fate of Himalayan glaciers. *Science*, **336(6079)**, 310-314.

Bosello, F., C. Carraro, and E.D. Cian, 2010: *Climate Policy and the Optimal Balance between Mitigation, Adaptation and Unavoided Damage.* Note di Lavoro 32.2010, Sustainable Development Series, Fondazione Eni Enrico Mattei, Milan, Italy, 28 pp.

Bosello, F., F. Eboli, and R. Pierfederici, 2012a: *Assessing the Economic Impacts of Climate Change – An Updated CGE Point of View.* Note di Lavoro 2.2012, Climate Change and Sustainable Development Series, Fondazione Eni Enrico Mattei, Milan, Italy, 26 pp.

Bosello, F., R. Nicholls, J. Richards, R. Roson, and R.S.J. Tol, 2012b: Economic impacts of climate change in Europe: sea-level rise. *Climatic Change*, **112(1)**, 63-81.

Bouchama, A. and J.P. Knochel, 2002: Heat stroke. *New England Journal of Medicine*, **346(25)**, 1978-1988.

Bouwer, L.M., R.P. Crompton, E. Faust, P. Höppe, and R.A. Pielke Jr., 2007: Confronting disaster losses. *Science*, **318(5851)**, 753.

Bouwer, L.M., P. Bubeck, and J.C.J.H. Aerts, 2010: Changes in future flood risk due to climate and development in a Dutch polder area. *Global Environmental Change*, **20(3)**, 463-471.

Bradley, B.A., D.M. Blumenthal, D.S. Wilcove, and L.H. Ziska, 2010: Predicting plant invasions in an era of global change. *Trends in Ecology & Evolution*, **25(5)**, 310-318.

Breton, M.-C., M. Garneau, I. Fortier, F. Guay, and J. Louis, 2006: Relationship between climate, pollen concentrations of *Ambrosia* and medical consultations for allergic rhinitis in Montreal, 1994-2002. *Science of the Total Environment*, **370(1)**, 39-50.

Brierley, A.S. and M.J. Kingsford, 2009: Impacts of climate change on marine organisms and ecosystems. *Current Biology*, **19(14)**, R602-R614.

Bringezu, S., H. Schütz, M. O'Brien, L. Kauppi, R.W. Howarth, and J. McNeely, 2009: *Towards Sustainable Production and Use of Resources: Assessing Biofuels.* Produced by the International Panel for Sustainable Resource Management, United Nations Environment Programme (UNEP), Paris, France, 118 pp.

Brisson, N., P. Gate, D. Gouache, G. Charmet, F. Oury, and F. Huard, 2010: Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. *Field Crops Research*, **119(1)**, 201-212.

Brito, D., 2008: Amphibian conservation: are we on the right track? *Biological Conservation*, **141(11)**, 2912-2917.

Brock, W.A. and S.R. Carpenter, 2010: Interacting regime shifts in ecosystems: implication for early warnings. *Ecological Monographs*, **80(3)**, 353-367.

Brodie, J., E. Post, and W.F. Laurance, 2012: Climate change and tropical biodiversity: a new focus. *Trends in Ecology & Evolution*, **27(3)**, 145-150.

Bruckner, T. and K. Zickfeld, 2009: Emissions corridors for reducing the risk of a collapse of the Atlantic thermohaline circulation. *Mitigation and Adaptation Strategies for Global Change*, **14(1)**, 61-83.

Brzoska, M., P.M. Link, A. Maas, and J. Scheffran (eds.), 2012: Editorial. Geoengineering: an issue for peace and security studies? *Sicherheit & Frieden / Security & Peace*, **30(4 SI)**, IV.

Budyko, M.I. and D.H. Miller, 1974: *Climate and Life*. Vol. 18 of the International Geophysics Series, Academic Press, Inc., London, UK, 508 pp.

Buhaug, H., 2010: Climate not to blame for African civil wars. *Proceedings of the National Academy of Sciences of the United States of America*, **107(38)**, 16477-16482.

Burke, M. and D. Lobell, 2010: Climate effects on food security: an overview. In: *Climate Change and Food Security: Adapting Agriculture to a Warmer World* [Lobell, D. and M. Burke (eds.)]. Springer, New York, pp. 199.

Burke, M.B., E. Miguel, S. Satyanath, J.A. Dykema, and D.B. Lobell, 2009: Warming increases the risk of civil war in Africa. *Proceedings of the National Academy of Sciences of the United States of America*, **106(49)**, 20670-20674.

Burney, J.A., S.J. Davis, and D.B. Lobell, 2010: Greenhouse gas mitigation by agricultural intensification. *Proceedings of the National Academy of Sciences of the United States of America*, **107(26)**, 12052-12057.

Burton, I., J. Wilson, and R.E. Munn, 1983: Environmental impact assessment: national approaches and international needs. *Environmental Monitoring and Assessment*, **3(2)**, 133-150.

Burton, I., R.W. Kates, and G.F. White, 1993: *The Environment as Hazard.* Guilford Press, New York, NY, USA, 290 pp.

Byrnes, J.E., P.L. Reynolds, and J.J. Stachowicz, 2007: Invasions and extinctions reshape coastal marine food webs. *PLOS ONE*, **3**, e295, doi:10.1371/journal.pone.0000295.

Campbell, J., D. Lobell, and C. Field, 2009: Greater transportation energy and GHG offsets from bioelectricity than ethanol. *Science*, **324(5930)**, 1055-1057.

Canadell, J.G. and M.R. Raupach, 2008: Managing forests for climate change mitigation. *Science*, **320(5882)**, 1456-1457.

Cançado, J.E.D., P.H.N. Saldiva, L.A.A. Pereira, L.B.L.S. Lara, P. Artaxo, L.A. Martinello, M.A. Arbex, A. Zanobetti, and A.L.F. Braga, 2006: The impact of sugar cane-burning emissions on the respiratory system of children and the elderly. *Environmental Health Perspectives*, **114(5)**, 725-729.

Cannon, T., 1994: Vulnerability analysis and the explanation of 'natural' disasters. In: *Disasters, Development and Environment* [Varley, A. (ed.)]. John Wiley & Sons, Chichester, UK, pp. 13-29.

Cannon, T., 2006: Vulnerability analysis, livelihoods and disasters. In: *Coping with Risks Due to Natural Hazards in the 21st Century* [Ammann, W.J., S. Dannenmann, and L. Vulliet (eds.)]. Taylor and Francis/Balkema, Leiden, Netherlands, pp. 41-49.

Cardinale, B.J., J.E. Duffy, A. Gonzalez, D.U. Hooper, C. Perrings, P. Venail, A. Narwani, G.M. Mace, D. Tilman, D.A. Wardle, A.P. Kinzig, G.C. Daily, M. Loreau, J.B. Grace, A. Larigauderie, D.S. Srivastava, and S. Naeem, 2012: Biodiversity loss and its impact on humanity. *Nature*, **486**, 59-67.

Cardona, O.D., 1986: Estudios de vulnerabilidad y evaluación del riesgo sísmico: planificación física y urbana en áreas propensas. *Boletín Técnico de la Asociación Colombiana de Ingeniería Sismica*, **33(2)**, 32-65.

Cardona, O.D., 1990: Terminología de Uso Común en Manejo de Riesgos. AGID Reporte No. 13, Escuela de Administración, Finanzas, y Tecnología, Medellín, Colombia.

Cardona, O.D., 2006: A system of indicators for disaster risk management in the Americas. In: *Measuring Vulnerability to Hazards of Natural Origin: Towards Disaster Resilient Societies* [Birkmann, J. (ed.)]. United Nations University Press, Tokyo, Japan, pp. 189-209.

Cardona, O.D., 2008: *Indicators of Disaster Risk and Risk Management: Program for Latin America and the Caribbean – Summary Report – Second Edition.* INE-08-002, Infrastructure and Environment Sector, Inter-American Development Bank, Washington, DC, USA, 44 pp.

Cardona, O.D., 2010: *Indicators of Disaster Risk and Risk Management – Program for Latin America and the Caribbean: Summary Report.* Evaluación de Riesgos Naturales – Latino America, ERN-AL, Environment, Rural Development and Disaster Risk Management Division (INE/RND), Technical Notes No. IDB-TN-169, Inter-American Development Bank, Washington, DC, USA, 37 pp.

Cardona, O.D., 2011: Disaster risk and vulnerability: concepts and measurement of human and environmental insecurity. In: *Coping with Global Environmental Change, Disasters and Security* [Brauch, H.G., Ú. Oswald Spring, C. Mesjasz, J. Grin, P. Kameri-Mbote, B. Chourou, P. Dunay, and J. Birkmann, eds.)]. Springer, Berlin Heidelberg, pp. 107-121.

Cardona, O.D., M.K. van Aalst, J. Birkmann, M. Fordham, G. McGregor, R. Perez, R.S. Pulwarty, E.L.F. Schipper, and B.T. Sinh, 2012: Determinants of risk: exposure and vulnerability. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K.

Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 65-108.

Chakraborty, S. and A.C. Newton, 2011: Climate change, plant diseases and food security: an overview. *Plant Pathology*, **60(1)**, 2-14.

Chandy, L. and G. Gertz, 2011: *Poverty in Numbers: The Changing State of Global Poverty from 2005 to 2015.* Policy Brief 2011-01, The Brookings Institution, Washington, DC, USA, 23 pp.

Chen, C., B. McCarl, and C. Chang, 2012: Climate change, sea level rise and rice: global market implications. *Climatic Change*, **110(3)**, 543-560.

Chenoweth, J., P. Hadjinicolaou, A. Bruggeman, J. Lelieveld, Z. Levin, M.A. Lange, E. Xoplaki, and M. Hadjikakou, 2011: Impact of climate change on the water resources of the eastern Mediterranean and Middle East region: modeled 21st century changes and implications. *Water Resources Research*, **47(6)**, W06506, doi:10.1029/2010WR010269.

Cherubini, F. and S. Ulgiati, 2010: Crop residues as raw materials for biorefinery systems –a LCA case study. *Applied Energy*, **87(1)**, 47-57.

Cherubini, F., N.D. Bird, A. Cowie, G. Jungmeier, B. Schlamadinger, and S. Woess-Gallasch, 2009: Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: key issues, ranges and recommendations. *Resources, Conservation and Recycling*, **53(8)**, 434-447.

Cheung, W.W.L., V.W.Y. Lam, J.L. Sarmiento, K. Kearney, R. Watson, and D. Pauly, 2009: Projecting global marine biodiversity impacts under climate change scenarios. *Fish and Fisheries*, **10(3)**, 235-251.

Cheung, W.W.L., J.L. Sarmiento, J. Dunne, T.L. Frölicher, V.W. Lam, M.D. Palomares, R. Watson, and D. Pauly, 2013: Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. *Nature Climate Change*, **3(5)**, 254-258.

Chivian, E. and A. Bernstein, 2008: *Sustaining Life: How Human Health Depends on Biodiversity.* Oxford University Press, New York, NY, USA, 542 pp.

Ciscar, J.C., A. Iglesias, L. Feyen, L. Szabó, D. Van Regemorter, B. Amelung, R. Nicholls, P. Watkiss, O.B. Christensen, R. Dankers, L. Garrote, C.M. Goodess, A. Hunt, A. Moreno, J. Richards, and A. Soria, 2011: Physical and economic consequences of climate change in Europe. *Proceedings of the National Academy of Sciences of the United States of America*, **108(7)**, 2678-2683.

Clarke, L., J. Edmonds, V. Krey, R. Richels, S. Rose, and M. Tavoni, 2009: International climate policy architectures: overview of the EMF 22 international scenarios. *Energy Economics*, **31(Suppl. 2)**, S64-S81.

Clements, D. and A. Ditommaso, 2011: Climate change and weed adaptation: can evolution of invasive plants lead to greater range expansion than forecasted? *Weed Research*, **51(3)**, 227-240.

Clot, B., 2003: Trends in airborne pollen: an overview of 21 years of data in Neuchâtel (Switzerland). *Aerobiologia*, **19(3)**, 227-234.

Comfort, L., B. Wisner, S. Cutter, R. Pulwarty, K. Hewitt, A. Oliver-Smith, J. Wiener, M. Fordham, W. Peacock, and F. Krimgold, 1999: Reframing disaster policy: the global evolution of vulnerable communities. *Global Environmental Change Part B: Environmental Hazards*, **1(1)**, 39-44.

Conde, D.A., N. Flesness, F. Colchero, O.R. Jones, and A. Scheuerlein, 2011: An emerging role of zoos to conserve biodiversity. *Science*, **331(6023)**, 1390-1391.

Copeland, C., 2005: *Hurricane-Damaged Drinking Water and Wastewater Facilities: Impacts, Needs, and Response.* CRS Report for Congress, RS22285, Congressional Research Service (CRS), Library of Congress, 6 pp.

Costa, L. and J.P. Kropp, 2013: Linking components of vulnerability in theoretic frameworks and case studies. *Sustainability Science*, **8(1)**, 1-9.

Cotrufo, M.F., M.J.I. Briones, and P. Ineson, 1998: Elevated CO_2 affects field decomposition rate and palatability of tree leaf litter: importance of changes in substrate quality. *Soil Biology and Biochemistry*, **30(12)**, 1565-1571.

Cox, P.M., D. Pearson, B.B. Booth, P. Friedlingstein, C. Huntingford, C.D. Jones, and C.M. Luke, 2013: Sensitivity of tropical carbon to climate change constrained by carbon dioxide variability. *Nature*, **494**, 341-344.

Cressey, D., 2008: Pushing the modelling envelope. *Nature News*, doi:10.1038/news.2008.1108.

Crowl, T.A., T.O. Crist, R.R. Parmenter, G. Belovsky, and A.E. Lugo, 2008: The spread of invasive species and infectious disease as drivers of ecosystem change. *Frontiers in Ecology and the Environment*, **6(5)**, 238-246.

Crowley, P., 2011: Interpreting 'dangerous' in the United Nations Framework Convention On Climate Change and the human rights of Inuit. *Regional Environmental Change*, **11(Suppl. 1)**, S265-S274.

Cutter, S.L. and C. Finch, 2008: Temporal and spatial changes in social vulnerability to natural hazards. *Proceedings of the National Academy of Sciences of the United States of America*, **105(7)**, 2301-2306.

Cutter, S.L., L. Barnes, M. Berry, C. Burton, E. Evans, E. Tate, and J. Webb, 2008: A place-based model for understanding community resilience to natural disasters. *Global Environmental Change*, **18(4)**, 598-606.

D'Amato, G., L. Cecchi, M. D'Amato, and G. Liccardi, 2010: Urban air pollution and climate change as environmental risk factors of respiratory allergy: an update. *Journal of Investigative Allergology and Clinical Immunology*, **20(2)**, 95-102.

Damialis, A., J.M. Halley, D. Gioulekas, and D. Vokou, 2007: Long-term trends in atmospheric pollen levels in the city of Thessaloniki, Greece. *Atmospheric Environment*, **41(33)**, 7011-7021.

Dankers, R., N.W. Arnell, D.B. Clark, P.D. Falloon, B.M. Fekete, S.N. Gosling, J. Heinke, H. Kim, Y. Masaki, Y. Satoh, T. Stacke, W. Yoshihide, and D. Wisser, 2013: A first look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble. *Proceedings of the National Academy of Sciences of the Unites States of America*, published ahead of print 16 December 2013, doi:10.1073/pnas.1302078110.

Dasgupta, S., B. Laplante, S. Murray, and D. Wheeler, 2009: *Sea-Level Rise and Storm Surges: A Comparative Analysis of Impacts in Developing Countries.* Policy Research Working Paper No. 4901, the Environment and Energy Team, Development Research Group, The World Bank, Washington, DC, USA, 41 pp.

Dauber, J., C. Brown, A.L. Fernando, J. Finnan, E. Krasuska, J. Ponitka, D. Styles, D. Thrän, K.J. Van Groenigen, and M. Weih, 2012: Bioenergy from "surplus" land: environmental and socio-economic implications. *BioRisk*, **7**, 5-50.

de Bruin, K., R. Dellink, and R.S.J. Tol, 2009: AD-DICE: an implementation of adaptation in the DICE model. *Climatic Change*, **95(1)**, 63-81.

de Sherbinin, A., 2014: Climate change hotspots mapping: what have we learned? *Climatic Change,* **123(1)**, 23-37.

De'ath, G., K.E. Fabricius, H. Sweatman, and M. Puotinen, 2012: The 27-year decline of coral cover on the Great Barrier Reef and its causes. *Proceedings of the National Academy of Sciences of the United States of America*, **109(44)**, 17995-17999.

Dell, M., B.F. Jones, and B.A. Olken, 2012: Temperature shocks and economic growth: evidence from the last half century. *American Economic Journal: Macroeconomics*, **4(3)**, 66-95.

den Elzen, M.G.J. and D.P. van Vuuren, 2007: Peaking profiles for achieving long-term temperature targets with more likelihood at lower costs. *Proceedings of the National Academy of Sciences of the United States of America*, **104(46)**, 17931-17936.

den Elzen, M.G.J., M. Meinshausen, and D.P. van Vuuren, 2007: Multi-gas emission envelopes to meet greenhouse gas concentration targets: costs versus certainty of limiting temperature increase. *Global Environmental Change*, **17(2)**, 260-280.

den Elzen, M.G., D.P. van Vuuren, and J. van Vliet, 2010: Postponing emission reductions from 2020 to 2030 increases climate risks and long-term costs. *Climatic Change*, **99(1-2)**, 313-320.

DEFRA, 2012: *UK Climate Change Risk Assessment: Government Report.* UK Department for Environment, Food and Rural Affairs (DEFRA), The Stationary Office, London, UK, 43 pp.

Díaz, S., J. Fargione, F.S. Chapin III, and D. Tilman, 2006: Biodiversity loss threatens human well-being. *PLOS Biology*, **4(8)**, e277, doi:10.1371/journal.pbio.0040277.

Diffenbaugh, N.S., F. Giorgi, L. Raymond, and X. Bi, 2007: Indicators of 21st century socioclimatic exposure. *Proceedings of the National Academy of Sciences of the United States of America*, **104(51)**, 20195-20198.

DiTomaso, J.M., J.N. Barney, and A.M. Fox, 2007: *Biofuel Feedstocks: The Risk of Future Invasions*. All U.S. Government Documents (Utah Regional Depository), Paper 79, CAST Commentary QTA 2007-1, Council for Agricultural Science and Technology (CAST), Ames, IA, USA, 9 pp., digitalcommons.usu.edu/govdocs/79.

Donner, S.D. and C.J. Kucharik, 2008: Corn-based ethanol production compromises goal of reducing nitrogen export by the Mississippi River. *Proceedings of the National Academy of Sciences of the United States of America*, **105(11)**, 4513-4518.

Dossena, M., G. Yvon-Durocher, J. Grey, J.M. Montoya, D.M. Perkins, M. Trimmer, and G. Woodward, 2012: Warming alters community size structure and ecosystem functioning. *Proceedings of the Royal Society B*, **279(1740)**, 3011-3019.

Douglas, I., 2009: Climate change, flooding and food security in south Asia. *Food Security*, **1(2)**, 127-136.

Douglas, I., K. Alam, M. Maghenda, Y. Mcdonnell, L. McLean, and J. Campbell, 2008: Unjust waters: climate change, flooding and the urban poor in Africa. *Environment and Urbanization*, **20(1)**, 187-205.

Douglas, M. and A. Wildavsky, 1982: *Risk and Culture: An Essay on the Selection of Technological and Environmental Dangers.* University of California Press, Berkeley, CA, USA, 224 pp.

Dullinger, S., A. Gattringer, W. Thuiller, D. Moser, N.E. Zimmermann, A. Guisan, W. Willner, C. Plutznar, M. Leitner, T. Mang, M. Caccianiga, T. Dirnboeck, S. Ertl, A. Fischer, J. Lenior, J.-C. Svenning, A. Psomas, D.R. Schmatz, U. Silc, P. Vittoz, and K. Huelber, 2012: Extinction debt of high-mountain plants under twenty-first century climate change. *Nature Climate Change*, **2**, 619-622.

Dutton, A. and K. Lambeck, 2012: Ice volume and sea level during the last interglacial. *Science*, **337(6091)**, 216-219.

Easterling, W.E., P.K. Aggarwal, P. Batima, K.M. Brander, L. Erda, S.M. Howden, A. Kirilenko, J. Morton, J.-F. Soussana, J. Schmidhuber, and F.N. Tubiello, 2007: Food, fibre and forest products. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contributions of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 273-313.

Edenhofer, O., B. Knopf, T. Barker, L. Baumstark, E. Bellevrat, B. Chateau, P. Criqui, M. Isaac, A. Kitous, S. Kypreos, M. Leimbach, K. Lessmann, B. Mange, S. Scrieciu, H. Turton, and D.P. Van Vuuren, 2010: The economics of low stabilization: model comparison of mitigation strategies and costs. *The Energy Journal*, **31(SI)**, 11-48.

EIA, 2013: *Monthly Energy Review, September 2013*. DOE/EIA-0035(2013/09), U.S. Energy Information Administration (EIA), Washington, DC, USA, 201 pp.

Elliott, J.R. and J. Pais, 2006: Race, class, and Hurricane Katrina: social differences in human responses to disaster. *Social Science Research*, **35(2)**, 295-321.

Enarson, E. and B.H. Morrow, 1998: *The Gendered Terrain of Disaster: Through Women's Eyes*. Praeger Publishers, Westport, CT, USA, 275 pp.

English, J.M., O.B. Toon, and M.J. Mills, 2012: Microphysical simulations of sulfur burdens from stratospheric sulfur geoengineering. *Atmospheric Chemistry and Physics*, **12(10)**, 4775-4793.

Erbs, M., R. Manderscheid, G. Jansen, S. Seddig, A. Pacholski, and H. Weigel, 2010: Effects of free-air CO_2 enrichment and nitrogen supply on grain quality parameters and elemental composition of wheat and barley grown in a crop rotation. *Agriculture, Ecosystems & Environment*, **136(1-2)**, 59-68.

Ericson, J.P., C.J. Vörösmarty, S.L. Dingman, L.G. Ward, and M. Meybeck, 2006: Effective sea-level rise and deltas: causes of change and human dimension implications. *Global and Planetary Change*, **50(1-2)**, 63-82.

Fang, Y., D.L. Mauzerall, J. Lui, A.M. Fiore, and L.W. Horowitz, 2013: Impacts of 21st century climate change on global air pollution-related premature mortality. *Climatic Change*, **121(2)**, 239-253, doi:10.1007/s10584-013-0847-8.

FAO, 2012: *The State of Food Insecurity in the World – Economic Growth is Necessary but not Sufficient to Accelerate Reduction of Hunger and Malnutrition.* Food and Agricultural Organization of the United Nations (FAO), Rome, Italy, 61 pp.

Fargione, J., 2010: Is bioenergy for the birds? An evaluation of alternative future bioenergy landscapes. *Proceedings of the National Academy of Sciences of the United States of America*, **107(44)**, 18745-18746.

Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne, 2008: Land clearing and the biofuel carbon debt. *Science*, **319(5867)**, 1235-1238.

Feyen, L., J.I. Barredo, and R. Dankers, 2009: Implications of global warming and urban land use change on flooding in Europe. In: *Water & Urban Development Paradigms – Towards an Integration of Engineering, Design and Management Approaches* [Feyen, J., K. Shannon, and M. Neville (eds.)]. CRC Press/Balkema, Leiden, Netherlands, pp. 217-225.

Fingerman, K.R., M.S. Torn, M.H. O'Hare, and D.M. Kammen, 2010: Accounting for the water impacts of ethanol production. *Environmental Research Letters*, **5(1)**, 014020, doi:10.1088/1748-9326/5/1/014020.

Fischlin, A., G.F. Midgley, J. Price, R. Leemans, B. Gopal, C. Turley, M. Rounsevall, P. Dube, J. Tarazona, and A. Velichko, 2007: Ecosystems, their properties, goods, and services. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 211-272.

Fitzherbert, E.B., M.J. Struebig, A. Morel, F. Danielsen, C.A. Brühl, P.F. Donald, and B. Phalan, 2008: How will oil palm expansion affect biodiversity? *Trends in Ecology and Evolution*, **23(10)**, 538-545.

Flannigan, M., B. Stocks, M. Turetsky, and M. Wotton, 2009: Impacts of climate change on fire activity and fire management in the circumboreal forest. *Global Change Biology*, **15(3)**, 549-560.

Fleming, J.R., 2010: *Fixing the Sky: The Checkered History of Weather and Climate Control.* Columbia University Press, Chichester, UK and New York, NY, USA, 325 pp.

Fletcher Jr., R.J., B.A. Robertson, J. Evans, P.J. Doran, J.R.R. Alavalapati, and D.W. Schemske, 2011: Biodiversity conservation in the era of biofuels: risks and opportunities. *Frontiers in Ecology and the Environment*, **9**, 161-168.

Foden, W.B., S.H.M. Butchart, S.N. Stuart, J.-C. Vié, H.R. Akçakaya, A. Angulo, L.M. Devantier, A. Gutsche, E. Turak, L. Cao, S.D. Donner, V. Katariya, R. Bernard, R.A. Holland, A.F. Hughes, S.E. O'Hanlon, S.T. Garnett, Ç.H. Şekercioğlu, and G.M. Mace, 2013: Identifying the world's most climate change vulnerable species: a systematic trait-based assessment of all birds, amphibians and corals. *PLOS ONE*, **8(6)**, e65427, doi:10.1371/journal.pone.0065427.

Fordham, D. and B. Brook, 2010: Why tropical island endemics are acutely susceptible to global change. *Biodiversity and Conservation*, **19(2)**, 329-342.

Fordham, M.H., 1998: Making women visible in disasters: problematising the private domain. *Disasters*, **22(2)**, 126-143.

Foreign Policy Group, 2012: *The Failed State Index 2012 – Interactive Map and Rankings*. The Foreign Policy (FP) Group, a division of the Washington Post Company, Washington, DC, USA, www.foreignpolicy.com/failed_states_index_2012_interactive.

Foresight, 2011: Migration and Global Environmental Change. Final Project Report. The Government Office for Science, London, UK, 236 pp. https://www.gov.uk/government/publications/migration-and-global-environmental-change-future-challenges-and-opportunities.

Frankhauser, S., J.B. Smith, and R.S.J. Tol, 1999: Weathering climate change: some simple rules to guide adaptation decisions. *Ecological Economics*, **30(1)**, 67-78.

Förster, H., T. Sterzel, C.A. Pape, M. Moneo-Lain, I. Niemeyer, R. Boer, and J.P. Kropp, 2011: Sea-level rise in Indonesia: on adaptation priorities in the agricultural sector. *Regional Environmental Change*, **11(4)**, 893-904.

Fothergill, A., E.G.M. Maestas, and J.D. Darlington, 1999: Race, ethnicity and disasters in the United States: a review of the literature. *Disasters*, **23(2)**, 156-173.

Frei, T. and E. Gassner, 2008: Climate change and its impact on birch pollen quantities and the start of the pollen season an example from Switzerland for the period 1969-2006. *International Journal of Biometeorology*, **52(7)**, 667-674.

Fuchs, R., M. Conran, and E. Louis, 2011: Climate change and Asia's coastal urban cities: can they meet the challenge? *Environment and Urbanization Asia*, **2(1)**, 13-28.

Funabashi, Y. and K. Kitazawa, 2012: Fukushima in review: a complex disaster, a disastrous response. *Bulletin of the Atomic Scientists*, **68(2)**, 9-21.

Fund for Peace, 2012: *The Failed States Index 2012*. The Fund for Peace, Washington, DC, USA, 48 pp.

Fung, F., A. Lopez, and M. New, 2011: Water availability in +2°C and +4°C worlds. *Philosophical Transactions of the Royal Society A*, **369(1934)**, 99-116.

Füssel, H.-M., 2009: *Review and Quantitative Analysis of Indices of Climate Change Exposure, Adaptive Capacity, Sensitivity, and Impacts.* Background note to the World Development Report 2010, World Bank, Washington, DC, USA, 34 pp.

Füssel, H.-M., 2010: Modeling impacts and adaptation in global IAMs. *Wiley Interdisciplinary Reviews: Climate Change*, **1(2)**, 288-303.

Füssel, H.-M. and R.J. Klein, 2006: Climate change vulnerability assessments: an evolution of conceptual thinking. *Climatic Change*, **75(3)**, 301-329.

Galán, C., H. García-Mozo, L. Vázquez, L. Ruiz, C.D. de la Guardia, and M.M. Trigo, 2005: Heat requirement for the onset of the *Olea europaea* L. pollen season in several sites in Andalusia and the effect of the expected future climate change. *International Journal of Biometeorology*, **49(3)**, 184-188.

Gallai, N., J.-M. Salles, J. Settele, and B.E. Vaissiere, 2009: Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecological Economics*, **68**, 810-821.

Garamszegi, L.Z., 2011: Climate change increases the risk of malaria in birds. *Global Change Biology*, **17(5)**, 1751-1759.

Garcia-Mozo, H., C. Galán, V. Jato, J. Belmonte, C. Díaz de la Guardia, D. Fernández, M. Gutiérrez, M. Aira, J. Roure, L. Ruiz, M. Trigo, and E. Domínguez-Vilches, 2006: *Quercus* pollen season dynamics in the Iberian Peninsula: response to meteorological parameters and possible consequences of climate change. *Annals of Agricultural and Environmental Medicine*, **13(2)**, 209-224.

Garschagen, M., 2013: Resilience and organisational institutionalism from a cross-cultural perspective: an exploration based on urban climate change adaptation in Vietnam. *Natural Hazards*, **67(1)**, 25-46.

Garschagen, M. and F. Kraas, 2011: Urban climate change adaptation in the context of transformation: lessons from Vietnam. In: *Resilient Cities* [Otto-Zimmerman, K. (ed.)]. Local Sustainability, Vol. 1, Springer Science, Dordrecht, Netherlands, pp. 131-139.

Garschagen, M. and P. Romero-Lankao, 2013: Exploring the relationships between urbanization trends and climate change vulnerability. *Climatic Change*, published online 15 August 2013, doi:10.1007/s10584-013-0812-6, pp. 16.

Gaston, K.J. and R.A. Fuller, 2008: Commonness, population depletion and conservation biology. *Trends in Ecology & Evolution*, **23(1)**, 14-19.

Gerten, D., J. Heinke, H. Hoff, H. Biemans, M. Fader, and K. Waha, 2011: Global water availability and requirements for future food production. *Journal of Hydrometeorology*, **12(5)**, 885-899.

Gerten, D., W. Lucht, S. Ostberg, J. Heinke, M. Kowarsch, H. Kreft, Z.W. Kundzewicz, J. Rastgooy, R. Warren, and H.-J. Schellnhuber, 2013: Asynchronous exposure to global warming: freshwater resources and terrestrial ecosystems. *Environmental Research Letters*, **8**, 034032, doi:10.1088/1748-9326/8/3/034032.

Giannini, T.C., A.L. Acosta, C.A. Garófalo, A.M. Saraiva, I. Alves-dos-Santos, and V.L. Imperatriz-Fonseca, 2012: Pollination services at risk: bee habitats will decrease owing to climate change in Brazil. *Ecological Modelling*, **244**, 127-131.

Goes, M., N. Tuana, and K. Keller, 2011: The economics (or lack thereof) of aerosol geoengineering. *Climatic Change*, **109(3-4)**, 719-744.

Gonzalez, P., R.P. Neilson, J.M. Lenihan, and R.J. Drapek, 2010: Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change. *Global Ecology and Biogeography*, **19**, 755-768.

Gosling, S.N. and N.W. Arnell, 2013: A global assessment of the impact of climate change on water scarcity. *Climatic Change*, published online 17 August 2013, doi:10.1007/s10584-013-0853-x.

Gosling, S., G. McGregor, and J. Lowe, 2009: Climate change and heat-related mortality in six cities Part 2: climate model evaluation and projected impacts from changes in the mean and variability of temperature with climate change. *International Journal of Biometeorology*, **53(1)**, 31-51.

Grassini, P. and K.G. Cassman, 2012: High-yield maize with large net energy yield and small global warming intensity. *Proceedings of the National Academy of Sciences of the United States of America*, **109(4)**, 1074-1079.

Green, R.E., Y.C. Collingham, S.G. Willis, R.D. Gregory, K.W. Smith, and B. Huntley, 2008: Performance of climate envelope models in retrodicting recent changes in bird population size from observed climatic change. *Biology Letters*, **4(5)**, 599-602.

Green, T.R., M. Taniguchi, H. Kooi, J.J. Gurdak, D.M. Allen, K.M. Hiscock, H. Treidel, and A. Aureli, 2011: Beneath the surface of global change: impacts of climate change on groundwater. *Journal of Hydrology*, **405(3-4)**, 532-560.

Grothmann, T. and A. Patt, 2005: Adaptive capacity and human cognition: the process of individual adaptation to climate change. *Global Environmental Change*, **15(3)**, 199-213.

Guariguata, M.R., C. García-Fernández, D. Sheil, R. Nasi, C. Herrero-Jáuregui, P. Cronkleton, and V. Ingram, 2010: Compatibility of timber and non-timber forest product management in natural tropical forests: perspectives, challenges, and opportunities. *Forest Ecology and Management*, **259(3)**, 237-245.

Guillerminet, M.L. and R.S.J. Tol, 2008: Decision making under catastrophic risk and learning: the case of the possible collapse of the West Antarctic Ice Sheet. *Climatic Change*, **91(1-2)**, 193-209.

Guttal, V. and C. Jayaprakash, 2009: Spatial variance and spatial skewness: leading indicators of regime shifts in spatial ecological systems. *Theoretical Ecology*, **2(1)**, 3-12.

Hallegatte, S., V. Przyluski, and A. Vogt-Schilb, 2011: Building world narratives for climate change impact, adaptation and vulnerability analyses. *Nature Climate Change*, **1(3)**, 151-155.

Hallegatte, S., C. Green, R.J. Nicholls, and J. Corfee-Morlot, 2013: Future flood losses in major coastal cities. *Nature Climate Change*, **3**, 802-806.

Hare, B., 2006: Relationship between increases in global mean temperature and impacts on ecosystems, food production, water, and socio-economic systems. In: *Avoiding Dangerous Climate Change* [Schellnhuber H.J., W. Cramer, N. Nakicenovich, T. Wigley, and G. Yohe (eds.)]. Cambridge University Press, Cambridge, UK, pp. 177-185.

Hare, W., J. Lowe, J. Rogelj, E. Sawin, and D. van Vuuren, 2010: Which emission pathways are consistent with a 2°C or 1.5°C temperature limit? In: *The Emissions Gap Report. Are the Copenhagen Accord Pledges Sufficient to Limit Global Warming to 2°C or 1.5°C? A Preliminary Assessment.* United Nations Environment Programme (UNEP), Nairobi, Kenya, pp. 23-30.

Harte, J. and J. Kitzes, 2012: The use and misuse of species-area relationships in predicting climate-driven extinction. In: *Saving a Million Species* [Hannah, L. (ed.)]. Island Press, Washington, DC, USA, pp. 73-86.

Hashizume, M., Y. Wagatsuma, A.S.G. Faruque, D.A. Sack, T. Hayashi, P.R. Hunter, and B. Armstrong, 2008: Factors determining vulnerability to diarrhea during and after severe floods in Bangladesh. *Journal of Water and Health*, **6(3)**, 323-332.

Haywood, J.M., A. Jones, N. Bellouin, and D. Stephenson, 2013: Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall. *Nature Climate Change*, **3**, 660-665.

He, F. and S.P. Hubbell, 2011: Species-area relationships always overestimate extinction rates from habitat loss. *Nature*, **473(7347)**, 368-371.

Heckendorn, P., D. Weisenstein, S. Fueglistaler, B. Luo, E. Rozanov, M. Schraner, L. Thomason, and T. Peter, 2009: The impact of geoengineering aerosols on stratospheric temperature and ozone. *Environmental Research Letters*, **4(4)**, 045108, doi:10.1088/1748-9326/4/4/045108.

Hegland, S.J., A. Nielsen, A. Lázaro, A. Bjerknes, and Ø. Totland, 2009: How does climate warming affect plant-pollinator interactions? *Ecology Letters*, **12(2)**, 184-195.

Heine, J. and A. Thompson (eds.), 2011: *Fixing Haiti: MINUSTAH and Beyond.* United Nations University Press, Tokyo, Japan, 277 pp.

Hertel, T.W., M.B. Burke, and D.B. Lobell, 2010: The poverty implications of climate-induced crop yield changes by 2030. *Global Environmental Change*, **20(4)**, 577-585.

Hewitt, C.N., A.R. MacKenzie, P. Di Carlo, C.F. Di Marco, J.R. Dorsey, M. Evans, D. Fowler, M.W. Gallagher, J.R. Hopkins, C.E. Jones, B. Langford, J.D. Lee, A.C. Lewis, S.F. Lim, J. McQuaid, P. Misztal, S.J. Moller, P.S. Monks, E. Nemitz, D.E. Oram, S.M. Owen, G.J. Phillips, T.A.M. Pugh, J.A. Pyle, C.E. Reeves, J. Ryder, J. Siong, U. Skiba, and D.J. Stewart, 2009: Nitrogen management is essential to prevent tropical oil palm plantations from causing ground-level ozone pollution. *Proceedings of the National Academy of Sciences of the United States of America*, **106(44)**, 18447-18451.

Hidalgo, F.D., S. Naidu, S. Nichter, and N. Richardson, 2010: Economic determinants of land invasions. *Review of Economics and Statistics*, **92(3)**, 505-523.

Hinkel, J., R. Nicholls, A. Vafeidis, R.S.J. Tol, and T. Avagianou, 2010: Assessing risk of and adaptation to sea-level rise in the European Union: an application of DIVA. *Mitigation and Adaptation Strategies for Global Change*, **15(7)**, 703-719.

Hoegh-Guldberg, O., 2012: The adaptation of coral reefs to climate change: is the Red Queen being outpaced? *Scientia Marina*, **76(2)**, 403-408.

Holdschlag, A. and B.M. Ratter, 2013: Multiscale system dynamics of humans and nature in The Bahamas: perturbation, knowledge, panarchy and resilience. *Sustainability Science*, **8(3)**, 407-421.

Hope, C., 2006: The marginal impact of CO_2 from PAGE2002: an integrated assessment model incorporating the IPCC's five reasons for concern. *Integrated Assessment Journal*, **6(1)**, 19-56.

Houghton, R.M.E., 2009: Domestic violence reporting and disasters in New Zealand. *Regional Development Dialogue*, **30(1)**, 79-90.

Hsiang, S.M. and M. Burke, 2014: Climate, conflict, and social stability: what does the evidence say? *Climatic Change*, **123(1)**, 39-55.

Hsiang, S.M., K.C. Meng, and M.A. Cane, 2011: Civil conflicts are associated with the global climate. *Nature*, **476(7361)**, 438-441.

Hsiang, S.M., M. Burke, and E. Miguel, 2013: Quantifying the influence of climate on human conflict. *Science*, **341(6151)**, 1235367.

Huang, T.C., Y.T. Hsu, and Y.C. Chou, 2010: Influence of climate change on the incidence of rice diseases and our adaptive strategies. *Plant Protection Bulletin*, **52**, 25-42.

Hughes, B.B., M.T. Irfan, H. Khan, K.B. Kumar, D.S. Rothman, and J.R. Solórzano, 2009: *Reducing Global Poverty: Patterns of Potential Human Progress*. Vol. 1, Paradigm, Boulder, CO, USA and Oxford University Press, New Delhi, India, 334 pp.

Hunter, C.M., H. Caswell, M.C. Runge, E.V. Regehr, S.C. Amstrup, and I. Stirling, 2010: Climate change threatens polar bear populations: a stochastic demographic analysis. *Ecology*, **91(10)**, 2883-2897.

Huntley, B. and P. Barnard, 2012: Potential impacts of climatic change on southern African birds of fynbos and grassland biodiversity hotspots. *Diversity and Distributions*, **18**, 769-781.

Hutchins, D.A., M.R. Mulholland, and F. Fu, 2009: Nutrient cycles and marine microbes in a CO_2-enriched ocean. *Oceanography*, **22(4)**, 128-145.

Hutton, C.W., S. Kienberger, F. Amoako Johnson, A. Allan, V. Giannini, and R. Allen, 2011: Vulnerability to climate change: people, place and exposure to hazard. *Advances in Science and Research*, **7(1)**, 37-45.

Hymans, S.H. and H.T. Shapiro, 1976: The allocation of household income to food consumption. *Journal of Econometrics*, **4(2)**, 167-188.

ICSU-LAC, 2010a: Science for a better life: developing regional scientific programs in priority areas for Latin America and the Caribbean, Vol. 2. In: *Understanding*

and Managing Risk Associated with Natural Hazards: An Integrated Scientific Approach in Latin America and the Caribbean [Cardona, O.D., J.C. Bertoni, T. Gibbs, M. Hermelin, and A. Lavell (eds.)]. ICSU-LAC / CONACYT, Rio de Janeiro, Brazil and Mexico City, Mexico, 87 pp.

ICSU-LAC, 2010b: Science for a better life: developing regional scientific programs in priority areas for Latin America and the Caribbean, Vol. 1. In: *Biodiversity in Latin America and the Caribbean: An Assessment of Knowledge, Research Scope and Priority Areas* [Arroyo, K.T., R. Dirzo, J.C. Castillas, F. Cejas, and C.A Joly (eds.)]. ICSU-LAC / CONACYT, Rio de Janeiro, Brazil and Mexico City, Mexico, 232 pp.

Idso, S.B. and K.E. Idso, 2001: Effects of atmospheric CO_2 enrichment on plant constituents related to animal and human health. *Environmental and Experimental Botany*, **45(2)**, 179-199.

Iglesias, A., S. Quiroga, M. Moneo, and L. Garrote, 2012: From climate change impacts to the development of adaptation strategies: challenges for agriculture in Europe. *Climatic Change*, **112(1)**, 143-168.

Immerzeel, W.W., L.P. van Beek, and M.F. Bierkens, 2010: Climate change will affect the Asian water towers. *Science*, **328(5984)**, 1382-1385.

Immerzeel, W., F. Pellicciotti, and M. Bierkens, 2013: Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds. *Nature Geoscience*, **6(9)**, 742-745.

IPCC, 2007a: *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K. and A. Reisinger (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

IPCC, 2007b: *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Metz, B., O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyers (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 890 pp.

IPCC, 2011: *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Prepared by Working Group III of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, and C. von Stechow (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1075 pp.

IPCC, 2012a: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp.

IPCC, 2012b: *Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Geoengineering* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, C. Field, V. Barros, T.F. Stocker, Q. Dahe, J. Minx, K. Mach, G.-K. Plattner, S. Schlömer, G. Hansen, and M. Mastrandrea (eds.)]. IPCC Working Group III Technical Support Unit, Potsdam Institute for Climate Impact Research, Potsdam, Germany, 99 pp.

IPCC, 2012c: Summary for Policymakers. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1-19.

Izrael, Y.A. and S.M. Semenov, 2006: Critical levels of greenhouse gases, stabilization scenarios, and implications for the global decisions. In: *Avoiding Dangerous Climate Change* [Schellnhuber, H.J., W. Cramer, N. Nakicenovic, T.M.L. Wigley, and G.W. Yohe (eds.)]. Cambridge University Press, New York, NY, USA, pp. 73-79.

Izrael, Y.A., A. Ryaboshapko, and N. Petrov, 2009: Comparative analysis of geo-engineering approaches to climate stabilization. *Russian Meteorology and Hydrology*, **34(6)**, 335-347.

Jabry, A., 2003: *Children in Disasters: After the Cameras have Gone.* Plan UK, London, UK, 56 pp.

Jankowska, M.M., D. Lopez-Carr, C. Funk, G.J. Husak, and Z.A. Chafe, 2012: Climate change and human health: spatial modeling of water availability, malnutrition, and livelihoods in Mali, Africa. *Applied Geography*, **33**, 4 15.

Johannessen, O. and M. Miles, 2011: Critical vulnerabilities of marine and sea ice-based ecosystems in the high Arctic. *Regional Environmental Change*, **11(Suppl. 1)**, S239-S248.

Jones, A., J.M. Haywood, K. Alterskjær, O. Boucher, J.N.S. Cole, C.L. Curry, P.J. Irvine, D. Ji, B. Kravitz, J. Egill Kristjánsson, J.C. Moore, U. Niemeier, A. Robock, H. Schmidt, B. Singh, S. Tilmes, S. Watanabe, and J.-H. Yoon, 2013: The impact of abrupt suspension of solar radiation management (termination effect) in experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research: Atmospheres*, **118(17)**, 9743-9752, doi:10.1002/jgrd.50762.

Jones, C., J. Lowe, S. Liddicoat, and R. Betts, 2009: Committed terrestrial ecosystem changes due to climate change. *Nature Geosciences*, **2(7)**, 484-487.

Jongman, B., P.J. Ward, and J.C. Aerts, 2012: Global exposure to river and coastal flooding: long term trends and changes. *Global Environmental Change*, **22(4)**, 823-835.

Jurgensone, I., J. Carstensen, A. Ikauniece, and B. Kalveka, 2011: Long-term changes and controlling factors of phytoplankton community in the Gulf of Riga (Baltic Sea). *Estuaries and Coasts*, **34(6)**, 1205-1219.

Kahan, D., 2010: Fixing the communications failure. *Nature*, **463(7279)**, 296-297.

Kahn, M.E., 2005: The death toll from natural disasters: the role of income, geography, and institutions. *The Review of Economics and Statistics*, **87(2)**, 271-284.

Kainuma, M., Y. Matsuoka, T. Masui, K. Takahashi, J. Fujino, and Y. Hijioka, 2007: Climate policy assessment using the Asia-Pacific Integrated Model. In: *Human-Induced Climate Change* [Schlesinger, M., H. Kheshgi, and J. Smith (eds.)]. Cambridge University Press, New York, NY, USA, pp. 314-327.

Karamessini, M., 2010: Life stage transitions and the still-critical role of the family in Greece. In: *The Welfare State and Life Transitions: A European Perspective* [Anzo, D., G. Bosch, and J. Rubery (eds.)]. Edward Elgar, Cheltenham, UK, pp. 257-283.

Kaser, G., M. Großhauser, and B. Marzeion, 2010: Contribution potential of glaciers to water availability in different climate regimes. *Proceedings of the National Academy of Sciences of the United States of America*, **107(47)**, 20223-20227.

Kasperson, R.E. and J.X. Kasperson, 2001: *Climate Change, Vulnerability and Social Justice.* Risk and Vulnerability Programme, Stockholm Environment Institute (SEI), Stockholm, Sweden, 18 pp.

Kasperson, R.E., O. Renn, P. Slovic, H.S. Brown, J. Emel, R. Goble, J.X. Kasperson, and S. Ratick, 1988: The social amplification of risk: a conceptual framework. *Risk Analysis*, **8(2)**, 177-187.

Kearney, M., R. Shine, and W.P. Porter, 2009: The potential for behavioral thermoregulation to buffer "cold-blooded" animals against climate warming. *Proceedings of the National Academy of Sciences of the United States of America*, **106(10)**, 3835-3840.

Keesing, F., L.K. Belden, P. Daszak, A. Dobson, C.D. Harvell, R.D. Holt, P. Hudson, A. Jolles, K.E. Jones, C.E. Mitchell, S.S. Myers, T. Bogich, and R.S. Ostfeld, 2010: Impacts of biodiversity on the emergence and transmission of infectious diseases. *Nature*, **468(7324)**, 647-652.

Kéfi, S., M. Rietkerk, C.L. Alados, Y. Pueyo, V.P. Papanastasis, A. ElAich, and P.C. de Ruiter, 2007: Spatial vegetation patterns and imminent desertification in Mediterranean arid ecosystems. *Nature*, **449**, 213-218.

Kelic, A., V. Loose, V. Vargas, and E. Vugrin, 2009: *Energy and Water Sector Policy Strategies for Drought Mitigation*. SAND 2009-1360, Sandia National Laboratories, Albuquerque, NM, USA, 71 pp.

Keller, K. and D. McInerney, 2008: The dynamics of learning about a climate threshold. *Climate Dynamics*, **30(2-3)**, 321-332.

Keller, K., B.M. Bolker, and D.F. Bradford, 2004: Uncertain climate thresholds and optimal economic growth. *Journal of Environmental Economics and Management*, **48(1)**, 723-741.

Keller, K., M. Hall, S. Kim, D. Bradford, and M. Oppenheimer, 2005: Avoiding dangerous anthropogenic interference with the climate system. *Climatic Change*, **73(3)**, 227-238.

Keller, K., G. Yohe, and M. Schlesinger, 2008: Managing the risks of climate thresholds: uncertainties and information needs. *Climatic Change*, **91(1)**, 5-10.

Kelly, P.M. and W.N. Adger, 2000: Theory and practice in assessing vulnerability to climate change and facilitating adaptation. *Climatic Change*, **47(4)**, 325-352.

Khanna, M., C.L. Crago, and M. Black, 2011: Can biofuels be a solution to climate change? The implications of land use change related emissions for policy. *Interface Focus*, **1**, 233-247.

Khazai, B., J.E. Daniel, and F. Wenzel, 2011: The March 2011 Japan Earthquake – analysis of losses, impacts, and implications for the understanding of risks posed by extreme events. *Technikfolgenabschätzung – Theorie Und Praxis*, **20(3)**, 22-33.

Khosla, R. and K.K. Guntupalli, 1999: Heat-related illnesses. *Critical Care Clinics*, **15(2)**, 251-263.

Khunwishit, S. and S. Arlikatti, 2012: Demographic changes in the United States of America: challenges for disaster management. In: *Opportunities and Challenges for Applied Demography in the 21st Century.* [Hoque, N. and D. Swanson (eds.)]. Applied Demography Series, Vol. 2, Springer Science, Dordrecht, Netherlands, pp. 273-288.

Kienberger, S., 2012: Spatial modelling of social and economic vulnerability to floods at the district level in Búzi, Mozambique. *Natural Hazards*, **64(3)**, 2001-2019.

Kittel, T., B. Baker, J. Higgins, and J. Haney, 2011: Climate vulnerability of ecosystems and landscapes on Alaska's North Slope. *Regional Environmental Change*, **11(Suppl. 1)**, S249-S264.

Klausmeyer, K.R. and M.R. Shaw, 2009: Climate change, habitat loss, protected areas and the climate adaptation potential of species in Mediterranean ecosystems worldwide. *PLOS ONE*, **4(7)**, e6392, doi:10.1371/journal.pone.0006392.

Klinenberg, E., 2002: *Heat Wave: A Social Autopsy of Disaster in Chicago.* The University of Chicago Press, Chicago, IL, USA, 305 pp.

Knopf, B., O. Edenhofer, C. Flachsland, M.T.J. Kok, H. Lotze-Campen, G. Luderer, A. Popp, and D.P. van Vuuren, 2010: Managing the low-carbon transition – from model results to policies. *The Energy Journal*, **31(SI 1)**, 223-245.

Knowlton, K., B. Lynn, R.A. Goldberg, C. Rosenzweig, C. Hogrefe, J.K. Rosenthal, and P.L. Kinney, 2007: Projecting heat-related mortality impacts under a changing climate in the New York City region. *American Journal of Public Health*, **97(11)**, 2028-2034.

Kocmánková, E., M. Trnka, J. Eitzinger, H. Formayer, M. Dubrovský, D. Semerádová, Z. Žalud, J. Juroch, and M. Možný, 2010: Estimating the impact of climate change on the occurrence of selected pests in the Central European region. *Climate Research*, **44(1)**, 95-105.

Koeller, P., C. Fuentes-Yaco, T. Platt, S. Sathyendranath, A. Richards, P. Ouellet, D. Orr, U. Skúladóttir, K. Wieland, L. Savard, and M. Aschan, 2009: Basin-scale coherence in phenology of shrimps and phytoplankton in the North Atlantic Ocean. *Science*, **324(5928)**, 791-793.

Koh, L.P., J. Ghazoul, R.A. Butler, W.F. Laurance, N.S. Sodhi, J. Mateo-Vega, and C.J.A. Bradshaw, 2010: Wash and spin cycle threats to tropical biodiversity. *Biotropica*, **42(1)**, 67-71.

Konzmann, M., D. Gerten, and J. Heinke, 2013: Climate impacts on global irrigation requirements under 19 GCMs, simulated with a vegetation and hydrology model. *Hydrological Sciences Journal*, **58(1)**, 88-105.

Kopp, R.E. and B.K. Mignone, 2012: The U.S. government's social cost of carbon estimates after their first two years: pathways for improvement. *Economics: The Open-Access, Open Assessment E-Journal*, **6**, 2012-15.

Kopp, R.E., F.J. Simons, J.X. Mitrovica, A.C. Maloof, and M. Oppenheimer, 2009: Probabilistic assessment of sea level during the last interglacial stage. *Nature*, **462(7275)**, 863-867.

Kopp, R.E., A. Golub, N.O. Keohane, and C. Onda, 2012: The influence of the specification of climate change damages on the social cost of carbon. *Economics: The Open-Access, Open Assessment E-Journal*, **6**, 2012-2013.

Kovats, R.S. and R. Akhtar, 2008: Climate, climate change and human health in Asian cities. *Environment and Urbanization*, **20(1)**, 165-175.

Kovats, R.S. and S. Hajat, 2008: Heat stress and public health: a critical review. *Annual Review of Public Health*, **29**, 41-55.

Kravitz, B., K. Caldeira, O. Boucher, A. Robock, P.J. Rasch, K. Alterskjær, D.B. Karam, J.N. Cole, C.L. Curry, and J.M. Haywood, 2013: Climate model response from the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research: Atmospheres*, **118(15)**, 8320-8332.

Krawchuk, M.A., M.A. Moritz, M. Parisien, J. Van Dorn, and K. Hayhoe, 2009: Global pyrogeography: the current and future distribution of wildfire. *Plos One*, **4(4)**, e5102, doi:10.1371/journal.pone.0005102.

Krey, V. and K. Riahi, 2009: Implications of delayed participation and technology failure for the feasibility, costs, and likelihood of staying below temperature targets – greenhouse gas mitigation scenarios for the 21st century. *Energy Economics*, **31(Suppl. 2)**, S94-S106.

Krieger, D.J., 2001: *The Economic Value of Forest Ecosystem Services: A Review.* The Wilderness Society, Washington, DC, USA, 31 pp.

Kriegler, E., J.W. Hall, H. Held, R. Dawson, and H.J. Schellnhuber, 2009: Imprecise probability assessment of tipping points in the climate system. *Proceedings of the National Academy of Sciences of the United States of America*, **106(13)**, 5041-5046.

Kucharik, C.J. and S.P. Serbin, 2008: Impacts of recent climate change on Wisconsin corn and soybean yield trends. *Environmental Research Letters*, **3(3)**, 034003, doi:10.1088/1748-9326/3/3/034003.

Kuhlmann, M., D. Guo, R. Veldtman, and J. Donaldson, 2012: Consequences of warming up a hotspot: species range shifts within a centre of bee diversity. *Diversity and Distributions*, **18**, 885-897.

Kuruppu, N. and D. Liverman, 2011: Mental preparation for climate adaptation: the role of cognition and culture in enhancing adaptive capacity of water management in Kiribati. *Global Environmental Change*, **21(2)**, 657-669.

Ladeau, S.L. and J.S. Clark, 2006: Pollen production by *Pinus taeda* growing in elevated atmospheric CO_2. *Functional Ecology*, **20(3)**, 541-547.

Lam, V.W.Y., W.W.L. Cheung, W. Swartz, and U.R. Sumaila, 2012: Climate change impacts on fisheries in West Africa: implications for economic, food and nutritional security. *African Journal of Marine Science*, **34(1)**, 103-117.

Lapola, D.M., M.D. Oyama, and C.A. Nobre, 2009: Exploring the range of climate biome projections for tropical South America: the role of CO_2 fertilization and seasonality. *Global Biogeochemical Cycles*, **23(3)**, GB3003, doi:10.1029/2008GB003357.

Lapola, D.M., R. Schaldach, J. Alcamo, A. Boundeau, J. Koch, C. Koelking, and J.A. Priess, 2010: Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proceedings of the National Academy of the United States of America*, **107(8)**, 3388-3393, doi:10.1073/pnas.0907318107.

Lautze, S., J. Leaning, A. Raven-Roberts, R. Kent, and D. Mazurana, 2004: Assistance, protection, and governance networks in complex emergencies. *The Lancet*, **364(9451)**, 2134-2141.

Lavell, A., M. Oppenheimer, C. Diop, J. Hess, R. Lempert, J. Li, R. Muir-Wood, and S. Myeong, 2012: Climate change: new dimensions in disaster risk, exposure, vulnerability, and resilience. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 25-64.

Leichenko, R.M. and K.L. O'Brien, 2008: *Environmental Change and Globalization: Double Exposures.* Oxford University Press, New York, NY, USA, 192 pp.

Lenoir, J., J. Gegout, P. Marquet, P. De Ruffray, and H. Brisse, 2008: A significant upward shift in plant species optimum elevation during the 20th century. *Science*, **320(5884)**, 1768-1771.

Lenton, T.M., 2011a: Beyond 2°C: redefining dangerous climate change for physical systems. *Wiley Interdisciplinary Reviews: Climate Change*, **2(3)**, 451-461.

Lenton, T.M., 2011b: Early warning of climate tipping points. *Nature Climate Change*, **1(4)**, 201-209.

Lenton, T.M. and J. Ciscar, 2013: Integrating tipping points into climate impact assessments. *Climatic Change*, **117(3)**, 585-597.

Lenton, T.M. and N.E. Vaughan, 2009: The radiative forcing potential of different climate geoengineering options. *Atmospheric Chemistry and Physics*, **9**, 5539-5561.

Lenton, T.M., H. Held, E. Kriegler, J.W. Hall, W. Lucht, S. Rahmstorf, and H.J. Schellnhuber, 2008: Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences of the United States of America*, **105(6)**, 1786-1793.

Levermann, A., T. Albrecht, R. Winkelmann, M. Martin, M. Haseloff, and I. Joughin, 2012: Kinematic first-order calving law implies potential for abrupt ice-shelf retreat. *The Cryosphere*, **6(2)**, 273-286.

Li, Y., W. Ye, M. Wang, and X. Yan, 2009: Climate change and drought: a risk assessment of crop-yield impacts. *Climate Research*, **39**, 31-46.

Lilleør, H.B. and K. Van den Broeck, 2011: Economic drivers of migration and climate change in LDCs. *Global Environmental Change*, **21(Suppl. 1)**, S70-S81.

Lin, A., 2013: Does geoengineering present a moral hazard? *Ecology Law Quarterly*, **40**, 673-712.

Lin, N., K. Emanuel, M. Oppenheimer, and E. Vanmarcke, 2012: Physically based assessment of hurricane surge threat under climate change. *Nature Climate Change*, **2**, 462-467.

Lin, S., M. Luo, R.J. Walker, X. Liu, S. Hwang, and R. Chinery, 2009: Extreme high temperatures and hospital admissions for respiratory and cardiovascular diseases. *Epidemiology*, **20(5)**, 738-746.

Liu, X., J.R. Rohr, and Y. Li, 2013: Climate, vegetation, introduced hosts and trade shape a wildlife pandemic. *Proceedings of the Royal Society B*, **280(1753)**, 20122506, doi:10.1098/rspb.2012.2506.

Liverman, D.M., 1990: Vulnerability to global environmental change. In: *Understanding Global Environmental Change: The Contributions of Risk Analysis and Management* [Kasperson, R.E., K. Dow, D. Golding, and J.X. Kasperson (eds.)].

Report on an International Workshop, The Earth Transformed Programme, Clark University, Worcester, MA, USA, pp. 27-44, www.environment.arizona.edu/files/env/profiles/liverman/liverman-1990-kasperson-et-al.pdf.

Lloyd, I.D. and M. Oppenheimer, 2014: On the design of an international governance framework for geoengineering. *Global Environmental Politics*, **14(2)**, 45-63.

Lloyd, S.J., R.S. Kovats, and Z. Chalabi, 2011: Climate change, crop yields, and undernutrition: development of a model to quantify the impact of climate scenarios on child undernutrition. *Environmental Health Perspectives*, **119(12)**, 1817-1823.

Lobell, D.B., M.B. Burke, C. Tebaldi, M.D. Mastrandrea, W.P. Falcon, and R.L. Naylor, 2008: Prioritizing climate change adaptation needs for food security in 2030. *Science*, **319(5863)**, 607-610.

Lobell, D.B., W. Schlenker, and J. Costa-Roberts, 2011: Climate trends and global crop production since 1980. *Science*, **333(6042)**, 616-620.

Loomis, J., P. Kent, L. Strange, K. Fausch, and A. Covich, 2000: Measuring the total economic value of restoring ecosystem services in an impaired river basin: results from a contingent valuation survey. *Ecological Economics*, **33**, 103-117.

Lorenz, A., M. Schmidt, E. Kriegler, and H. Held, 2012: Anticipating climate threshold damages. *Environmental Modeling and Assessment*, **17(1)**, 163-175.

Loss, S.R., L.A. Terwilliger, and A.C. Peterson, 2011: Assisted colonization: integrating conservation strategies in the face of climate change. *Biological Conservation*, **144(1)**, 92-100.

Lotze-Campen, H., A. Popp, T. Beringer, C. Müller, A. Bondeau, S. Rost, and W. Lucht, 2010: Scenarios of global bioenergy production: the trade-offs between agricultural expansion, intensification and trade. *Ecological Modelling*, **221(18)**, 2188-2196.

Lough, J., 2012: Small change, big difference: sea surface temperature distributions for tropical coral reef ecosystems, 1950-2011. *Journal of Geophysical Research*, **117(C9)**, C09018, doi:10.1029/2012JC008199.

Lubchenco, J. and L. Petes, 2010: Eleventh Annual Roger Revelle Commemorative Lecture: the interconnected biosphere – science at the ocean's tipping points. *Oceanography*, **23(2)**, 115-129.

Luber, G. and M. McGeehin, 2008: Climate change and extreme heat events. *American Journal of Preventive Medicine*, **35(5)**, 429-435.

Lung, T., C. Lavalle, R. Hiederer, A. Dosio, and L.M. Bouwer, 2013: A multi-hazard regional level impact assessment for Europe combining indicators of climatic and non-climatic change. *Global Environmental Change*, **23(2)**, 522-536.

Luyssaert, S., E.-D. Schulze, A. Börner, A. Knohl, D. Hessenmöller, B.E. Law, P. Ciais, and J. Grace, 2008: Old-growth forests as global carbon sinks. *Nature*, **455**, 213-215.

Macknick, J., S. Sattler, S., K. Averyt, S. Clemmer, and J. Rogers, 2012: Water implications of generating electricity: water use across the United States based on different electricity pathways through 2050. *Environmental Research Letters*, **7(4)**, 045803, doi:10.1088/1748-9326/7/4/045803.

Maestre, F.T., J.L. Quero, N.J. Gotelli, A. Escudero, V. Ochoa, M. Delgado-Baquerizo, M. García-Gómez, M.A. Bowker, S. Soliveres, C. Escolar, P. García-Palacios, M. Berdugo, E. Valencia, B. Gozalo, A. Gallardo, L. Aguilera, T. Arredondo, J. Blones, B. Boeken, D. Bran, A.A. Conceição, O. Cabrera, M. Chaieb, M. Derak, D.J. Eldridge, C.I. Espinosa, A. Florentino, J. Gaitán, M.G. Gatica, W. Ghiloufi, S. Gómez-González, J.R. Gutiérrez, R.M. Hernández, X. Huang, E. Huber-Sannwald, M. Jankju, M. Miriti, J. Monerris, R.L. Mau, E. Morici, K. Naseri, A. Ospina, V. Polo, A. Prina, E. Pucheta, D.A. Ramírez-Collantes, R. Romão, M. Tighe, C. Torres-Díaz, J. Val, J.P. Veiga, D. Wang, and E. Zaady, 2012: Plant species richness and ecosystem multifunctionality in global drylands. *Science*, **335(6065)**, 214-218.

Magan, N., A. Medina, and D. Aldred, 2011: Possible climate-change effects on mycotoxin contamination of food crops pre- and postharvest. *Plant Pathology*, **60(1)**, 150-163.

Maiorano, L., A. Falcucci, N.E. Zimmermann, A. Psomas, J. Pottier, D. Baisero, C. Rondinini, A. Guisan, L. Boitani, and L. Maiorano, 2011: The future of terrestrial mammals in the Mediterranean basin under climate change. *Philosophical Transactions of the Royal Society B*, **366(1578)**, 2681-2692.

Malhi, Y., L.E.O.C. Aragão, D. Galbraith, C. Huntingford, R. Fisher, P. Zelazowski, S. Sitch, C. McSweeney, and P. Meir, 2009: Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences of the United States of America*, **106(49)**, 20610-20615, doi:10.1073/pnas.0804619106.

Mansilla, E., 1996: *Desastres Modelo Para Armar: Colección de Piezas de un Rompecabezas Social.* Red de Estudios Sociales en Prevención de Desastres en América Latin: La RED, Lima, Peru, 223 pp.

Mantyka-Pringle, C.S., T.G. Martin, and J.R. Rhodes, 2012: Interactions between climate and habitat loss effects on biodiversity: a systematic review and meta-analysis. *Global Change Biology*, **18(4)**, 1239-1252.

Maskrey, A., 1989: *Disaster Mitigation: A Community Based Approach.* Oxfam, Oxford, UK, 114 pp.

Maskrey, A., 1993a: Vulnerability accumulation in peripheral regions in Latin America: the challenge for disaster prevention and management. In: *Natural Disasters: Protecting Vulnerable Communities* [Merriman, P.A. and C.W. Browitt (eds.)]. Proceedings of the Conference Held in London, 13-15 October 1993, International Decade for Natural Disaster Reduction (IDNDR), Thomas Telford, London, UK, pp. 461-472.

Maskrey, A., 1993b: *Los Desastres: No son Naturales.* Red de Estudios Sociales en Prevención de Desastres en América Latina: LA RED, Tercer Mundo Editores, Bogata, Colombia, 137 pp.

Maskrey, A., 1994: Disaster mitigation as a crisis paradigm: reconstructing after the Alto Mayo Earthquake, Peru. In: *Disaster, Development and Environment* [Varley, A. (ed.)]. John Wiley & Sons, Chichester, UK, pp. 109-123.

Maskrey, A., 1998: *Navegando entre Brumas: La Aplicación de los Sistemas de Información Geográfica al Análisis de Riesgo en América Latina.* Red de Estudios Sociales en Prevención de Desastres en América Latina: LA RED, Intermediate Technology Development Group (ITDG-Perú), Lima, Peru, 344 pp.

Maskrey, A., 2011: Revisiting community-based disaster risk management. *Environmental Hazards*, **10(1)**, 42-52.

McAlpine, C.A., J.G. Ryan, L. Seabrook, S. Thomas, P.J. Dargusch, J.I. Syktus, R.A. Pielke Sr, A.E. Etter, P.M. Fearnside, and W.F. Laurance, 2010: More than CO_2: a broader paradigm for managing climate change and variability to avoid ecosystem collapse. *Current Opinion in Environmental Sustainability*, **2(5-6)**, 334-346.

McClellan, J., D.W. Keith, and J. Apt, 2012: Cost analysis of stratospheric albedo modification delivery systems. *Environmental Research Letters*, **7(3)**, 034019, doi:10.1088/1748-9326/7/3/034019.

McInerney, D. and K. Keller, 2008: Economically optimal risk reduction strategies in the face of uncertain climate thresholds. *Climatic Change*, **91(1)**, 29-41.

McInerney, D., R. Lempert, and K. Keller, 2012: What are robust strategies in the face of uncertain climate threshold responses? *Climatic Change*, **112(3)**, 547-568.

McKay, N.P., J.T. Overpeck, and B.L. Otto-Bliesner, 2011: The role of ocean thermal expansion in Last Interglacial sea level rise. *Geophysical Research Letters*, **38(14)**, doi:10.1029/2011GL048280.

McKenzie, D. and M.C. Kennedy, 2012: Power laws reveal phase transitions in landscape controls of fire regimes. *Nature Communications*, **3**, 726, doi:10.1038/ncomms1731.

McLeman, R., 2011: *Climate Change, Migration, and Critical International Security Considerations.* IOM Migration Research Series No. 42, International Organization for Migration (IOM), Geneva, Switzerland, 50 pp.

McLeod, K.L. and H.M. Leslie, 2009: Why ecosystem-based management? In: *Ecosystem-Based Management for the Oceans* [McLeod, K.L. and H.M. Leslie (ed.)]. Island Press, Washington, DC, USA, pp. 3-12.

McMahon, J. and S.K. Price, 2011: Water and energy interactions. *Annual Review of Environment and Resources*, **36**, 163-191.

McNeall, D., P.R. Halloran, P. Good, and R.A. Betts, 2011: Analyzing abrupt and nonlinear climate changes and their impacts. *Wiley Interdisciplinary Reviews: Climate Change*, **2(5)**, 663-686.

Meehl, G.A., W.M. Washington, J.M. Arblaster, A. Hu, H. Teng, C. Tebaldi, B.N. Sanderson, J. Lamarque, A. Conley, and W.G. Strand, 2012: Climate system response to external forcings and climate change projections in CCSM4. *Journal of Climate*, **25(11)**, 3661-3683.

Meinshausen, M., S.C.B. Raper, and T.M.L. Wigley, 2011: Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6: Part I – model description and calibration. *Atmospheric Chemistry and Physics*, **11**, 1417-1456.

Meissner, K., T. Lippmann, and A. Sen Gupta, 2012: Large-scale stress factors affecting coral reefs: open ocean sea surface temperature and surface seawater aragonite saturation over the next 400 years. *Coral Reefs*, **31(2)**, 309-319.

Melillo, J.M., J.M. Reilly, D.W. Kicklighter, A.C. Gurgel, T.W. Cronin, S. Paltsev, B.S. Felzer, X. Wang, A.P. Sokolov, and C.A. Schlosser, 2009a: Indirect emissions from biofuels: how important? *Science* **326(5958)**, 1397-1399.

Melillo, J.M., A.C. Gurgel, D.W. Kicklighter, J.M. Reilly, T.W. Cronin, B.S. Felzer, S. Paltsev, C.A. Schlosser, A.P. Sokolov, X. Wang, 2009b: *Unintended Environmental Consequences of a Global Biofuels Program*. Report No. 168. MIT Joint Program on the Science and Policy of Global Change, Cambridge, Massachusetts, USA, 34 pp., http://dspace.mit.edu/handle/1721.1/44626

Mendelsohn, R., K. Emanuel, S. Chonabayashi, and L. Bakkensen, 2012: The impact of climate change on global tropical cyclone damage. *Nature Climate Change*, **2(3)**, 205-209.

Menkhaus, K., 2010: Stabilisation and humanitarian access in a collapsed state: the Somali case. *Disasters*, **34(Suppl. S3)**, S320-S341.

Midgley, G.F., 2012: Biodiversity and ecosystem function. *Science*, **335(6065)**, 174-175.

Midgley, G.F. and W. Thuiller, 2011: Potential responses of terrestrial biodiversity in Southern Africa to anthropogenic climate change. *Regional Environmental Change*, **11(Suppl. 1)**, S127-S135.

Miettinen, J., A. Hooijer, C. Shi, D. Tollenaar, R. Vernimmen, S.C. Liew, C. Malins, and S.E. Page, 2012: Extent of industrial plantations on Southeast Asian peatlands in 2010 with analysis of historical expansion and future projections. *Global Change Biology Bioenergy*, **4(6)**, 908-918.

Millennium Ecosystem Assessment, 2005a: *Ecosystems and Human Well-Being: Our Human Planet: Summary for Decision-Makers.* A Report of the Millennium Ecosystem Assessment, Island Press, Washington, DC, USA, 109 pp.

Millennium Ecosystem Assessment, 2005b: *Ecosystems and Human Well-being: Synthesis.* A Report of the Millennium Ecosystem Assessment, Island Press, Washington, DC, USA, 137 pp.

MNP, 2006: *Intergrated Modelling of Global Environmental Change: An Overview of IMAGE 2.4* [Bouwman, A.F., T. Kram, and K. Klein Goldewijk (eds.)]. MNP publication number 500110002/2006, Netherlands Environmental Assessment Agency (MNP), Bilthoven, Netherlands, 228 pp.

Mohan, J.E., L.H. Ziska, W.H. Schlesinger, R.B. Thomas, R.C. Sicher, K. George, and J.S. Clark, 2006: Biomass and toxicity responses of poison ivy (*Toxicodendron radicans*) to elevated atmospheric CO_2. *Proceedings of the National Academy of Sciences of the United States of America*, **103(24)**, 9086-9089.

Mooney, H., A. Larigauderie, M. Cesario, T. Elmquist, O. Hoegh-Guldberg, S. Lavorel, G.M. Mace, M. Palmer, R. Scholes, and T. Yahara, 2009: Biodiversity, climate change, and ecosystem services. *Current Opinion in Environmental Sustainability*, **1(1)**, 46-54.

Morgan, M.G. and M. Henrion, 1990: *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis.* Cambridge University Press, Cambridge, UK, 332 pp.

Morrow, D.R., R.E. Kopp, and M. Oppenheimer, 2009: Toward ethical norms and institutions for climate engineering research. *Environmental Research Letters*, **4(4)**, 045106, doi:10.1088/1748-9326/4/4/045106.

Mougou, R., M. Mansour, A. Iglesias, R. Chebbi, and A. Battaglini, 2011: Climate change and agricultural vulnerability: a case study of rain-fed wheat in Kairouan, Central Tunisia. *Regional Environmental Change*, **11(Suppl. 1)**, S137-S142.

Müller, C., W. Cramer, W.L. Hare, and H. Lotze-Campen, 2011: Climate change risks for African agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, **108(11)**, 4313-4315.

Murphy, D.M., 2009: Effect of stratospheric aerosols on direct sunlight and implications for concentrating solar power. *Environmental Science & Technology*, **43(8)**, 2784-2786.

Murray, K.A., D. Rosauer, H. McCallum, and L.F. Skerratt, 2011: Integrating species traits with extrinsic threats: closing the gap between predicting and preventing species declines. *Proceedings of the Royal Society B*, **278(1711)**, 1515-1523.

Murray, S., P. Foster, and I. Prentice, 2012: Future global water resources with respect to climate change and water withdrawals as estimated by a dynamic global vegetation model. *Journal of Hydrology*, **448-449**, 14-29.

Narita, D., K. Rehdanz, and R.S.J. Tol, 2012: Economic costs of ocean acidification: a look into the impacts on global shellfish production. *Climatic Change*, **113**, 1049-1063.

National Research Council, 2010: *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean*. Committee on the Development of an Integrated Science Strategy for Ocean Acidification Monitoring, Research, and Impacts Assessment, Division on Earth and Life Studies, National Research Council, The National Academies Press, Washington, DC, USA, 188 pp.

National Research Council, 2011: *Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia.* Committee on Stabilization Targets for Atmospheric Greenhouse Gas Concentrations, Division on Earth and Life Studies, National Research Council, The National Academies Press, Washington, DC, USA, 286 pp.

UK NEA, 2011: *The UK National Ecosystem Assessment: Synthesis of the Key Findings.* UK National Ecosystem Assessment (UK NEA) Project, United Nations Environment Programme-World Conservation Monitoring Centre (UNEP-WCMC), Cambridge, UK, 87 pp.

Neal, D.M. and B.D. Phillips, 1990: Female-dominated local social movement organizations in disaster-threat situations. In: *Women and Social Protest* [West, G. and R.L. Blumberg (eds.)]. Oxford University Press, New York, NY, USA, pp. 243-255.

Nelson, G.C., M.W. Rosegrant, J. Koo, R. Robertson, T.B. Sulser, Z. Tingju, C. Ringler, S. Msangi, A. Palazzo, M. Batka, M. Magalhaes, R. Valmonte-Santos, M. Ewing, and D. Lee, 2009: *Climate Change: Impact on Agriculture and Costs of Adaptation.* International Food Policy Research Institute (IFPRI), Washington, DC, USA, 19 pp.

Nelson, G.C., M.W. Rosegrant, A. Palazzo, I. Gray, C. Ingersoll, R. Robertson, S. Tokgoz, T. Zhu, T.B. Sulser, C. Ringler, S. Msangi, and L. You, 2010: *Food Security, Farming, and Climate Change to 2050: Scenarios, Results, Policy Options.* International Food Policy Research Institute, Washington, DC, USA, 131 pp.

Neumayer, E. and T. Plümper, 2007: The gendered nature of natural disasters: the impact of catastrophic events on the gender gap in life expectancy, 1981-2002. *Annals of the Association of American Geographers*, **97(3)**, 551-566.

Nicholls, R.J. and A. Cazenave, 2010: Sea-level rise and its impact on coastal zones. *Science*, **328(5985)**, 1517-1520.

Nicholls, R.J. and C. Small, 2002: Improved estimates of coastal population and exposure to hazards released. *EOS, Transactions of the American Geophysical Union*, **83(28)**, 301-305, doi:10.1029/2002EO000216.

Nicholls, R.J. and R.S. Tol, 2006: Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century. *Philosophical Transactions of the Royal Society A*, **364(1841)**, 1073-1095.

Nicholls, R.J., R.S.J. Tol, and A. Vafeidis, 2008a: Global estimates of the impact of a collapse of the West Antarctic ice sheet: an application of FUND. *Climatic Change*, **91(1)**, 171-191.

Nicholls, R.J., S. Hanson, C. Herweijer, N. Patmore, S. Hallegatte, J. Corfee-Morlot, J. Château, and R. Muir-Wood, 2008b: *Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes: Exposure Estimates.* OECD Environment Working Papers, No.1, OECD Publishing, Paris, France, 62 pp., doi:10.1787/011766488208.

Nicholls, R.J., N. Marinova, J.A. Lowe, S. Brown, P. Vellinga, D. de Gusmão, J. Hinkel, and R.S.J. Tol, 2011: Sea-level rise and its possible impacts given a 'beyond 4°C world' in the twenty-first century. *Philosophical Transactions of the Royal Society A*, **369(1934)**, 161-181.

Norberg, J., M.C. Urban, M. Vellend, C.A. Klausmeier, and N. Loeuille, 2012: Eco-evolutionary responses of biodiversity to climate change. *Nature Climate Change*, **2**, 747-751.

Nordås, R. and N.P. Gleditsch, 2007: Climate change and conflict. *Political Geography*, **26(6)**, 627-638.

O'Brien, K., L. Sygna, R. Leichenko, W.N. Adger, J. Barnett, T. Mitchell, L. Schipper, T. Tanner, C. Vogel, and C. Mortreux, 2008: *Disaster Risk Reduction, Climate Change Adaptation and Human Security*. Report prepared for the Royal Norwegian Ministry of Foreign Affairs by the Global Environmental Change and Human Security (GECHS) Project, GECHS Report 2008:3, University of Oslo, Oslo, Norway, 76 pp.

O'Connor, F.M., O. Boucher, N. Gedney, C.D. Jones, G.A. Folberth, R. Coppell, P. Friedlingstein, W.J. Collins, J. Chappellaz, J. Ridley, and C.E. Johnson, 2010: Possible role of wetlands, permafrost, and methane hydrates in the methane cycle under future climate change: a review. *Reviews of Geophysics*, **48(4)**, RG4005, doi:10.1029/2010RG000326.

O'Connor, R., R. Bord, and A. Fisher, 1999: Risk perceptions, general environmental beliefs, and willingness to address climate change. *Risk Analysis* **19(3)**, 461-471.

O'Keefe, P., K. Westgate, and B. Wisner, 1976: Taking the naturalness out of natural disasters. *Nature*, **260**, 566-567.

O'Loughlin, J., F.D. Witmer, A.M. Linke, A. Laing, A. Gettelman, and J. Dudhia, 2012: Climate variability and conflict risk in East Africa, 1990-2009. *Proceedings of the National Academy of Sciences of the United States of America*, **109(45)**, 18344-18349.

O'Neill, B.C., K. Riahi, and I. Keppo, 2010: Mitigation implications of midcentury targets that preserve long-term climate policy options. *Proceedings of the National Academy of Sciences of the United States of America*, **107(3)**, 1011-1016.

O'Neill, B.C., E. Kriegler, K. Riahi, K.L. Ebi, S. Hallegatte, T.R. Carter, R. Mathur, and D.P. van Vuuren, 2014: A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change*, **122(3)**, 387-400.

O'Neill, M.S., 2003: Air conditioning and heat-related health effects. *Applied Environmental Science and Public Health*, **111(16)**, 1861-1870.

Oman, L., A. Robock, G. Stenchikov, G.A. Schmidt, and R. Ruedy, 2005: Climatic response to high-latitude volcanic eruptions. *Journal of Geophysical Research*, **110(D13)**, D13103, doi:10.1029/2004JD005487.

Oman, L., A. Robock, G.L. Stenchikov, and T. Thordarson, 2006: High-latitude eruptions cast shadow over the African monsoon and the flow of the Nile. *Geophysical Research Letters,* **33**, L18711, doi:10.1029/2006GL027665.

Oppenheimer, M., 2005: Defining dangerous anthropogenic interference: the role of science, the limits of science. *Risk Analysis*, **25(6)**, 1399-1407.

Oppenheimer, M., 2013: Climate change impacts: accounting for the human response. *Climatic Change*, **117(3)**, 439-449.

Oppenheimer, M., B. O'Neill, and M. Webster, 2008: Negative learning. *Climatic Change*, **89(1)**, 155-172.

Orlove, B., 2009: Glacier retreat: reviewing the limits of human adaptation to climate change. *Environment: Science and Policy for Sustainable Development*, **51(3)**, 22-34.

Parry, M.L., C. Rosenzweig, A. Iglesias, M. Livermore, and G. Fischer, 2004: Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change*, **14(1)**, 53-67.

Patt, A., D. van Vuuren, F. Berkhout, A. Aaheim, A. Hof, M. Isaac, and R. Mechler, 2010: Adaptation in integrated assessment modeling: where do we stand? *Climatic Change*, **99(3)**, 383-402.

Peacock, W., 1997: *Hurricane Andrew: Ethnicity, Gender and the Sociology of Disasters.* Routledge, Abingdon, UK and New York, NY, USA, 304 pp.

Pearman, P.B., A. Guisan, and N.E. Zimmermann, 2011: Impacts of climate change on Swiss biodiversity: an indicator taxa approach. *Biological Conservation*, **144(2)**, 866-875.

Peduzzi, P., B. Chatenoux, H. Dao, A. De Bono, C. Herold, J. Kossin, F. Mouton, and O. Nordbeck, 2012: Global trends in tropical cyclone risk. *Nature Climate Change*, **2(4)**, 289-294.

Pelling, M., 2010: *Adaptation to Climate Change: From Resilience to Transformation.* Routledge, Abingdon, UK and New York, NY, USA, 224 pp.

Pelling, M. and J.I. Uitto, 2001: Small island developing states: natural disaster vulnerability and global change. *Global Environmental Change Part B: Environmental Hazards*, **3(2)**, 49-62.

Pelling, M., C. High, J. Dearing, and D. Smith, 2008: Shadow spaces for social learning: a relational understanding of adaptive capacity to climate change within organizations. *Environment and Planning*, **40(4)**, 867-884.

Perch-Nielsen, S. (ed.), 2004: *Understanding the Effect of Climate Change on Human Migration: The Contribution of Mathematical and Conceptual Models.* Diploma Thesis, Department of Environmental Sciences, Swiss Federal Institute of Technology, Zurich, Switzerland, 113 pp.

Petzoldt, C. and A. Seaman, 2006: *Climate Change Effects on Insects and Pathogens.* New York State IPM Program, Geneva, New York, USA, 16 pp.

Phillips, O.L., L.E.O.C. Aragão, S.L. Lewis, J.B. Fisher, J. Lloyd, G. López-González, Y. Malhi, A. Monteagudo, J. Peacock, C.A. Quesada, G. van der Heijden, S. Almeida, I. Amaral, L. Arroyo, G. Aymard, T.R. Baker, O. Bánki, L. Blanc, D. Bonal, P. Brando, J. Chave, Á.C.A. de Oliveira, N.D. Cardozo, C.I. Czimczik, T.R. Feldpausch, M.A. Freitas, E. Gloor, N. Higuchi, E. Jiménez, G. Lloyd, P. Meir, C. Mendoza, A. Morel, D.A. Neill, D. Nepstad, S. Patiño, M.C. Peñuela, A. Prieto, F. Ramírez, M. Schwarz, J. Silva, M. Silveira, A.S. Thomas, H. ter Steege, J. Stropp, R. Vásquez, P. Zelazowski, E.A. Dávila, S. Andelman, A. Andrade, K.-J. Chao, T. Erwin, A. Di Fiore, E.H.C., H. Keeling, T.J. Killeen, W.F. Laurance, A.P. Cruz, N.C.A. Pitman, P.N. Vargas, H. Ramírez-Angulo, A. Rudas, R. Salamão, N. Silva, J. Terborgh, and A. Torres-Lezama, 2009: Drought sensitivity of the Amazon rainforest. *Science*, **323(5919)**, 1344-1347.

Pielke Jr., R.A., 1998: Rethinking the role of adaptation in climate policy. *Global Environmental Change*, **8(2)**, 159-170.

Pielke Jr., R.A., 2007: Future economic damage from tropical cyclones: sensitivities to societal and climate changes. *Philosophical Transactions of the Royal Society A*, **365(1860)**, 2717-2729.

Piguet, E., 2010: Linking climate change, environmental degradation, and migration: a methodological overview. *Wiley Interdisciplinary Reviews: Climate Change*, **1(4)**, 517-524.

Pimentel, D., R. Zuniga, and D. Morrison, 2005: Update on the environmental and economic costs associated with alien-invasive species in the United States. *Ecological Economics*, **52**, 273-288.

Pimentel, D., A. Marklein, M.A. Toth, M.N. Karpoff, G.S. Paul, R. McCormack, J. Kyriazis, and T. Krueger, 2009: Food versus biofuels: environmental and economic costs. *Human Ecology*, **37(1)**, 1-12.

Pimm, S.L., 2009: Climate disruption and biodiversity. *Current Biology*, **19(14)**, R595-R601.

Piontek, F., C. Müller, T.A.M. Pugh, D.B. Clark, D. Deryng, J. Elliott, F. de Jesus Colón González, M. Flörke, C. Folberth, W. Franssen, K. Frieler, A.D. Friend, S.N. Gosling, D. Hemming, N. Khabarov, H. Kim, M.R. Lomas, Y. Masaki, M. Mengel, A. Morse, K. Neumann, K. Nishina, S. Ostberg, R. Pavlick, A.C. Ruane, J. Schewe, E. Schmid, T. Stacke, Q. Tang, Z.D. Tessler, A.M. Tompkins, L. Warszawski, D. Wisser, and H.J. Schellnhuber, 2014: Multisectoral climate impact hotspots in a warming world. *Proceedings of the National Academy of Sciences of the United States of America*, **111(9)**, 3233-3238.

Pittock, J., 2011: National climate change policies and sustainable water management, conflicts and synergies. *Ecology and Society*, **16(2)**, 25, www.ecologyandsociety.org/vol16/iss2/art25/.

Plevin, R.J., 2009: Modeling corn ethanol and climate. *Journal of Industrial Ecology*, **13(4)**, 495-507.

Polasky, S., S.R. Carpenter, C. Folke, and B. Keeler, 2011: Decision-making under great uncertainty: environmental management in an era of global change. *Trends in Ecology & Evolution*, **26(8)**, 398-404.

Pongratz, J., D. Lobell, L. Cao, and K. Caldeira, 2012: Crop yields in a geoengineered climate. *Nature Climate Change*, **2(2)**, 101-105.

Portmann, F.T., P. Döll, S. Eisner, and M. Flörke, 2013: Impact of climate change on renewable groundwater resources: assessing the benefits of avoided greenhouse gas emissions using selected CMIP5 climate projections. *Environmental Research Letters*, **8(2)**, 024023, doi:10.1088/1748-9326/8/2/024023.

Poudel, B.N., K.P. Paudel, G. Timilsina, and D. Zilberman, 2012: Providing numbers for a food versus fuel debate: an analysis of a future biofuel production scenario. *Applied Economic Perspectives and Policy*, **24(4)**, 637-668.

Power, N.M. and J.D. Murphy, 2009: Which is the preferable transport fuel on a greenhouse gas basis; biomethane or ethanol? *Biomass and Bioenergy*, **33(10)**, 1403-1412.

Preston, B.L., 2013: Local path dependence of US socioeconomic exposure to climate extremes and the vulnerability commitment. *Global Environmental Change*, **23(4)**, *719-732*.

Raghu, S., R.C. Anderson, C.C. Daehler, A.S. Davis, R.N. Wiedenmann, D. Simberloff, and R.N. Mack, 2006: Adding biofuels to the invasive species fire? *Science*, **313(5794)**, 1742.

Randin, C.F., R. Engler, S. Normand, M. Zappa, N.E. Zimmermann, P.B. Pearman, P. Vittoz, W. Thuiller, and A. Guisan, 2009: Climate change and plant distribution: local models predict high-elevation persistence. *Global Change Biology*, **15(6)**, 1557-1569.

Ranger, N., 2011: Adaptation as a decision making under deep uncertainty. In: *Climate: Global Change and Local Adaptation* [Linkov, I. and T.S. Bridges (eds.)]. NATO Science for Peace and Security Series C: Environmental Security, Springer Science, Dordrecht, Netherlands, pp. 89-122.

Ranger, N., L. Gohar, J. Lowe, S. Raper, A. Bowen, and R. Ward, 2012: Is it possible to limit global warming to no more than 1.5°C? *Climatic Change*, **111(3)**, 973-981.

Ranson, M., 2012: *Crime, Weather, and Climate Change*. Harvard Kennedy School M-RCBG Associate Working Paper Series No. 8, Mossavar-Rahmani Center for Business & Government, Harvard Kennedy School, Cambridge, MA, USA, 50 pp.

Rasmussen, A., 2002: The effects of climate change on the birch pollen season in Denmark. *Aerobiologia*, **18(3)**, 253-265.

Ray-Bennett, N.S., 2009: The influence of caste, class and gender in surviving multiple disasters: a case study from Orissa, India. *Environmental Hazards*, **8(1)**, 5-22.

Reed, D.A., M.D. Powell, and J.M. Westerman, 2010: Energy infrastructure damage analysis for hurricane Rita. *Natural Hazards Review*, **11(3)**, 102-109.

Renaud, F., J. Birkmann, M. Damm, and G. Gallopín, 2010: Understanding multiple thresholds of coupled social-ecological systems exposed to natural hazards as external shocks. *Natural Hazards*, **55(3)**, 749-763.

Resources for the Future, 2009: *The Global Adaptation Atlas*. Online mapping tool developed by Resources for the Future in collaboration with a diverse network of partners, www.adaptationatlas.org.

Reuveny, R., 2007: Climate change-induced migration and violent conflict. *Political Geography*, **26(6)**, 656-673.

Rhomberg, M., 2009: *The Mass Media and the Risk Communication of Climate Change: A Theoretical Observation.* The Political Studies Association, London, UK, 28 pp.

Rinaldi, S.M., J.P. Peerenboom, and T.K. Kelly, 2001: Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems Magazine*, **21(6)**, 11-25.

Roberts, M.J. and W. Schlenker, 2013: Identifying supply and demand elasticities of agricultural commodities: implications for the US ethanol mandate. *American Economic Review*, **103(6)**, 2265-2295.

Robock, A., 2008a: Whither geoengineering? *Science*, **320(5880)**, 1166-1167.

Robock, A., 2008b: 20 Reasons why geoengineering may be a bad idea. *Bulletin of the Atomic Scientists*, **64(2)**, 14-18.

Robock, A., L. Oman, and G.L. Stenchikov, 2008: Regional climate responses to geoengineering with tropical and Arctic SO_2 injections. *Journal of Geophysical Research*, **113**, D16101, doi:10.1029/2008JD010050.

Robock, A., A. Marquardt, B. Kravitz, and G. Stenchikov, 2009: Benefits, risks, and costs of stratospheric geoengineering. *Geophysical Research Letters*, **36(19)**, L19703, doi:10.1029/2009GL039209.

Robock, A., D.G. MacMartin, R. Duren, and M.W. Christensen, 2013: Studying geoengineering with natural and anthropogenic analogs. *Climatic Change*, **121(3)**, 445-458.

Rogelj, J., M. Meinshausen, and R. Knutti, 2012: Global warming under old and new scenarios using IPCC climate sensitivity range estimates. *Nature Climate Change*, **2(4)**, 248-253.

Rogers, C.A., P.M. Wayne, E.A. Macklin, M.L. Muilenberg, C.J. Wagner, P.R. Epstein, and F.A. Bazzaz, 2006: Interaction of the onset of spring and elevated atmospheric CO_2 on ragweed (*Ambrosia artemisiifolia* L.) pollen production. *Environmental Health Perspectives*, **114(6)**, 865-869.

Rohr, J.R. and T.R. Raffel, 2010: Linking global climate and temperature variability to widespread amphibian declines putatively caused by disease. *Proceedings of the National Academy of Science of the United States of America*, **107(18)**, 8269-8274, doi:10.1073/pnas.0912883107.

Root, T.L. and S.H. Schneider, 2006: Conservation and climate change: the challenges ahead. *Conservation Biology*, **20(3)**, 706-708.

Rosenzweig, C. and D. Hillel, 2008: *Climate Variability and the Global Harvest: Impacts of El Nino and Other Oscillations on Agro-Ecosystems.* Oxford University Press, New York, NY, USA, 280 pp.

Roson, R. and D. Van der Mensbrugghe, 2012: Climate change and economic growth: impacts and interactions. *Int'l Journal of Sustainable Economy*, **4(3)**, 270-285.

Rothausen, S.G.S.A. and D. Conway, 2011: Greenhouse-gas emissions from energy use in the water sector. *Nature Climate Change*, **1(4)**, 210-219.

Rothman, D.S., P. Romero-Lankao, V.J. Schweizer, and B.A. Bee, 2014: Challenges to adaptation: a fundamental concept for the shared socio-economic pathways and beyond. Special Issue of *Climatic Change*, **122(3)**, 495-507.

Rötter, R.P., T.R. Carter, J.E. Olesen, and J.R. Porter, 2011: Crop-climate models need an overhaul. *Nature Climate Change*, **1(4)**, 175-177.

Rusin, N. and L. Flit, 1960: *Man Versus Climate.* Peace Publishers, Moscow, Russia, 175 pp.

Russell, L.M., P.J. Rasch, G.M. Mace, R.B. Jackson, J. Shepherd, P. Liss, M. Leinen, D. Schimel, N.E. Vaughan, A.C. Janetos, P.W. Boyd, R.J. Norby, K. Caldeira, J. Merikanto, P. Artaxo, J. Melillo, and M.G. Morgan, 2012: Ecosystem impacts of geoengineering: a review for developing a science plan. *Ambio,* **41(350-369)**, doi:10.1007/s13280-012-0258-5.

Sala, O.E., F.S. Chapin III, J.J. Armesto, E. Berlow, J. Bloomfield, R. Dirzo, E. Huber-Sanwald, L.F. Huenneke, R.B. Jackson, A. Kinzig, R. Leemans, D.M. Lodge, H.A. Mooney, M. Oesterheld, N. LeRoy Poff, M.T. Sykes, B.H. Walker, M. Walker, and D.H. Wall, 2000: Global biodiversity scenarios for the year 2100. *Science*, **287(5459)**, 1770-1774.

Salter, S., G. Sortino, and J. Latham, 2008: Sea-going hardware for the cloud albedo method of reversing global warming. *Philosophical Transactions of the Royal Society A*, **366(1882)**, 3989-4006.

Sander, K. and G.S. Murthy, 2010: Life cycle analysis of algae biodiesel. *The International Journal of Life Cycle Assessment*, **15(7)**, 704-714.

Scheffran, J., M. Brzoska, J. Kominek, P.M. Link, and J. Schilling, 2012: Climate change and violent conflict. *Science*, **336(6083)**, 869-871.

Schewe, J., J. Heinke, D. Gerten, I. Haddeland, N.W. Arnell, D.B. Clark, R. Dankers, S. Eisner, B.M. Fekete, F.J. Colón-González, S.N. Gosling, H. Kim, X. Liu, Y. Masaki, F.T. Portmann, Y. Satoh, T. Stacke, Q. Tang, Y. Wada, D. Wisser, T. Albrecht, K. Frieler, F. Piontek, L. Warszawski, and P. Kabat, 2013: Multi-model assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, published ahead of print 16 December 2013, doi:10.1073/pnas.1222460110.

Schmidhuber, J. and F.N. Tubiello, 2007: Climate change and food security special feature: global food security under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **104(50)**, 19703-19708.

Schmidt, H., K. Alterskjær, D. Bou Karam, O. Boucher, A. Jones, J.E. Kristjánsson, U. Niemeier, M. Schulz, A. Aaheim, F. Benduhn, M. Lawrence, and C. Timmreck, 2012: Can a reduction of solar irradiance counteract CO_2-induced climate change? – results from four Earth system models. *Earth System Dynamics*, **3**, 63-78.

Schneider, S.H., S. Semenov, A. Patwardhan, I. Burton, C.H.D. Magadza, M. Oppenheimer, A.B. Pittock, A. Rahman, J.B. Smith, A. Suarez, and F. Yamin, 2007: Assessing key vulnerabilities and the risk from climate change. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 779-810.

Schnitzler, J., J. Benzler, D. Altmann, I. Mücke, and G. Krause, 2007: Survey on the population's needs and the public health response during floods in Germany 2002. *Journal of Public Health Management and Practice*, **13(5)**, 461-464.

Schröter, D., 2005: Assessing vulnerabilities to the effects of global change: an eight step approach. *Mitigation and Adaptation Strategies for Global Change*, **10(4)**, 573-595.

Searchinger, T., R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T. Yu, 2008: Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, **319(5867)**, 1238-1240.

Şekercioğlu, Ç.H., 2008: Climate change, elevational range shifts, and bird extinctions. *Conservation Biology*, **22(1)**, 140-150.

Şekercioğlu, Ç.H., R.B. Primack, and J. Wormworth, 2012: The effects of climate change on tropical birds. *Biological Conservation*, **148(1)**, 1-18.

Selig, E.R., K.S. Casey, and J.F. Bruno, 2012: Temperature-driven coral decline: the role of marine protected areas. *Global Change Biology*, **18(5)**, 1561-1570.

Sen, A., 1981: *Poverty and Famines. An Essay on Entitlements and Deprivation.* Clarendon Press, Oxford, UK, 257 pp.

Shea, K.M., R.T. Truckner, R.W. Weber, and D.B. Peden, 2008: Climate change and allergic disease. *Journal of Allergy and Clinical Immunology*, **122(3)**, 443-453.

Shepard, C.C., C.M. Crain, and M.W. Beck, 2011: The protective role of coastal marches: a systemic review and meta-analysis. *PLOS ONE*, **6(11)**, e27374, doi:10.1371/journal.pone.0027374.

Shepherd, J., K. Caldeira, P. Cox, J. Haigh, D. Keith, B. Launder, G. Mace, G. MacKerron, J. Pyle, S. Rayner, C. Redgwell, and A. Watson, 2009: *Geoengineering the Climate: Science, Governance and Uncertainty.* The Royal Society, London, UK, 82 pp.

Sherwood, S.C. and M. Huber, 2010: An adaptability limit to climate change due to heat stress. *Proceedings of the National Academy of Sciences of the United States of America*, **107(21)**, 9552-9555.

Shi, Y., R.S. Wang, J.L. Huang, and W.R. Yang, 2012: An analysis of the spatial and temporal changes in Chinese terrestrial ecosystem service functions. *Chinese Science Bulletin*, **57(17)**, 2120-2131.

Sietz, D., M.K. Lüdeke, and C. Walther, 2011: Categorisation of typical vulnerability patterns in global drylands. *Global Environmental Change*, **21(2)**, 431-440.

Sietz, D., S.E. Manani Choque, and M.K.B. Lüdeke, 2012: Typical patterns of smallholder vulnerability to weather extremes with regard to food security in the Peruvian Altiplano. *Regional Environmental Change*, **12(3)**, 489-505.

Silverman, J., 2009: Coral reefs may start dissolving when atmospheric CO_2 doubles. *Geophysical Research Letters*, **36(5)**, L05606, doi:10.1029/2008GL036282.

Singer, B.D., L.H. Ziska, D.A. Frenz, D.E. Gebhard, and J.G. Straka, 2005: Increasing Amb a 1 content in common ragweed (*Ambrosia artemisiifolia*) pollen as a function of rising atmospheric CO_2 concentration. *Functional Plant Biology*, **32(7)**, 667-670.

Skaggs, R., K. Hibbard, P. Frumhoff, T. Lowry, R. Middleton, R. Pate, V. Tidwell, J. Arnold, K. Averyt, and A. Janetos, 2012: *Climate and Energy-Water-Land System Interactions*. Technical Report PNNL-21185 to the U.S. Department of Energy in support of the National Climate Assessment, Pacific Northwest National Laboratory, Richland, WA, USA, 152 pp.

Slovic, P., 1993: Perceived risk, trust, and democracy. *Risk Analysis*, **13(6)**, 675-682.

Slovic, P., 2010: *The Feeling of Risk: New Perspectives on Risk Perception.* Earthscan, London, UK, 425 pp.

Slovic, P., B. Fischoff, and S. Lichtenstein, 1982: Facts versus fears: understanding perceived risk. In: *Judgment Under Uncertainty: Heuristics and Biases* [Kahneman, D., P. Slovic, and A. Tversky (eds.)]. Cambridge University Press, New York, NY, USA, pp. 463-489.

Smit, B. and J. Wandel, 2006: Adaptation, adaptive capacity and vulnerability. *Global Environmental Change*, **16(3)**, 282-292.

Smit, B., I. Burton, R.J.T. Klein, and R. Street, 1999: The science of adaptation: a framework for assessment. *Mitigation and Adaptation Strategies for Global Change*, **4(3)**, 199-213.

Smith, J.B., H.-J. Schellnhuber, M.M.Q. Mirza, S. Fankhauser, R. Leemans, L. Erda, L. Ogallo, B. Pittock, R. Richels, C. Rosenzweig, U. Safriel, R.S.J. Tol, J. Weyant, and G.W. Yohe, 2001: Vulnerability to climate change and reasons for concern: a synthesis. In: *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [McCarthy, J.J., O.F. Canziani, N.A. Leary, D.J. Dokken, and J.S. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 913-967.

Smith, J.B., S.H. Schneider, M. Oppenheimer, G.W. Yohe, W. Hare, M.D. Mastrandrea, A. Patwardhan, I. Burton, J. Corfee-Morlot, C.H.D. Magadza, H.-M. Füssel, A.B. Pittock, A. Rahman, A. Suarez, and J.-P. van Ypersele, 2009: Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) "reasons for concern". *Proceedings of the National Academy of Sciences of the United States of America*, **106(11)**, 4133-4137.

Smith, P., H. Haberl, A. Popp, K.-h. Erb, C. Lauk, R. Harper, F.N. Tubiello, A. de Siquera Pinto, M. Jafari, S. Sohi, O. Masera, H. Böttcher, G. Berndes, M. Bustamante, H. Ahammad, H. Clark, H. Dong, E.A. Elsiddig, C. Mbow, N.H. Ravindranath, C.W. Rice, C.R. Abad, A. Romanovskaya, F. Sperling, M. Herrero, J.I. House, and S. Rose, 2013: How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Global Change Biology*, **19(8)**, 2285-2302.

Smithers, J. and B. Smit, 1997: Human adaptation to climatic variability and change. *Global Environmental Change*, **7(2)**, 129-146.

Solomon, S., 1999: Stratospheric ozone depletion: a review of concepts and history. *Reviews of Geophysics*, **37(3)**, 275-316.

Stafoggia, M., F. Forastiere, D. Agostini, A. Biggeri, L. Bisanti, E. Cadum, N. Caranci, F. de'Donato, S. De Lisio, M. De Maria, P. Michelozzi, R. Miglio, P. Pandolfi, S. Picciotto, M. Rognoni, A. Russo, C. Scarnato, and C.A. Perucci, 2006: Vulnerability to heat-related mortality: a multicity, population-based, case-crossover analysis. *Epidemiology*, **17(3)**, 315-323.

Stagg, C.L. and I.A. Mendelssohn, 2010: Restoring ecological function to a submerged salt marsh. *Restoration Ecology*, **18(Suppl. s1)**, 10-17.

Staudinger, M.D., N.B. Grimm, A. Staudt, S.L. Carter, F.S. Chapin III, P. Kareiva, M. Ruckelshaus, and B.A. Stein, 2012: *Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment.* Cooperative Report to the 2013 National Climate Assessment, United States Global Change Research Program, Washington, DC, USA, 296 pp.

Sterner, T. and U.M. Persson, 2008: An even sterner review: introducing relative prices into the discounting debate. *Review of Environmental Economics and Policy*, **2(1)**, 61-76.

Stover, E. and P. Vinck, 2008: Cyclone Nargis and the politics of relief and reconstruction aid in Burma (Myanmar). *JAMA: The Journal of the American Medical Association*, **300(6)**, 729-731.

Strzepek, K. and B. Boehlert, 2010: Competition for water for the food system. *Philosophical Transactions of the Royal Society B*, **365(1554)**, 2927-2940.

Stuart, S.N., J.S. Chanson, N.A. Cox, B.E. Young, A.S.L. Rodrigues, D.L. Fischman, and R.W. Waller, 2004: Status and trends of amphibian declines and extinctions worldwide. *Science*, **306(5702)**, 1783-1786.

Sultana, F., 2010: Living in hazardous waterscapes: gendered vulnerabilities and experiences of floods and disasters. *Environmental Hazards*, **9(1)**, 43-53.

Susman, P., P. O'Keefe, and B. Wisner, 1983: Global disasters, a radical interpretation. In: *Interpretations of Calamity* [Hewitt, K. (ed.)]. Allen & Unwin, Inc., Winchester, MA, USA, pp. 264-283.

Swart, R. and N. Marinova, 2010: Policy options in a worst case climate change world. *Mitigation and Adaptation Strategies for Global Change*, **15(6)**, 531-549.

Tacoli, C., 2009: Crisis or adaptation? Migration and climate change in a context of high mobility. *Environment and Urbanization*, **21(2)**, 513-525.

Tao, F., M. Yokozawa, J. Liu, and Z. Zhang, 2008: Climate-crop yield relationships at provincial scales in China and the impacts of recent climate trends. *Climate Research*, **38(1)**, 83-94.

Taub, D.R., B. Miller, and H. Allen, 2008: Effects of elevated CO_2 on the protein concentration of food crops: a meta-analysis. *Global Change Biology*, **14(3)**, 565-575.

te Linde, A.H., P. Bubeck, J.E.C. Dekkers, H. de Moel, and J.C.J.H. Aerts, 2011: Future flood risk estimates along the river Rhine. *Natural Hazards and Earth System Science*, **11(2)**, 459-473.

Theisen, O.M., H. Holtermann, and H. Buhaug, 2011: Climate wars? Assessing the claim that drought breeds conflict. *International Security*, **36(3)**, 79-106.

Thomalla, F., T. Downing, E. Spanger-Siegfried, G. Han, and J. Rockström, 2006: Reducing hazard vulnerability: towards a common approach between disaster risk reduction and climate adaptation. *Disasters*, **30(1)**, 39-48.

Thornton, P.K., P.G. Jones, P.J. Ericksen, and A.J. Challinor, 2011: Agriculture and food systems in sub-Saharan Africa in a 4°C+ world. *Philosophical Transactions of the Royal Society A*, **369(1934)**, 117-136.

Thywissen, K., 2006: Core terminology of disaster reduction: a comparative glossary. In: *Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies* [Birkmann, J. (ed.)]. United Nations University Press, Tokyo, Japan, pp. 448-484.

Tidwell, V.C., P.H. Kobos, L.A. Malczynski, G. Klise, and C.R. Castillo, 2011: Exploring the water-thermoelectric power Nexus. *Journal of Water Resources Planning and Management*, **138(5)**, 491-501.

Tilman, D., C. Balzer, J. Hill, and B.L. Befort, 2011: Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, **108(50)**, 20260-20264.

Tilmes, S., R. Müller, and R. Salawitch, 2008: The sensitivity of polar ozone depletion to proposed geoengineering schemes. *Science*, **320(5880)**, 1201-1204.

Tol, R.S.J., 2009: The feasibility of low concentration targets: an application of FUND. *Energy Economics*, **31(Suppl. 2)**, S121-S130.

Tol, R.S.J. and G.W. Yohe, 2006: Of dangerous climate change and dangerous emission reduction. In: *Avoiding Dangerous Climate Change* [Schellnhüber, H.J., W. Cramer, N. Nakicenovic, T.M.L. Wigley, and G.W. Yohe (eds.)]. Cambridge University Press, Cambridge, UK, pp. 291-298.

Toms, J.D., J. Faaborg, and W.J. Arendt, 2012: Climate change and birds in the forgotten tropics: the importance of tropical dry forests. *Ibis*, **154(3)**, 632-634.

Transparency International, 2012: *The Corruption Perception Index 2011.* Transparency International, Berlin, Germany, 7 pp.

Trenberth, K.E. and A. Dai, 2007: Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering. *Geophysical Research Letters*, **34(15)**, L15702, doi:10.1029/2007GL030524.

Tschakert, P. and K.A. Dietrich, 2010: Anticipatory learning for climate change adaptation and resilience. *Ecology and Society*, **15(2)**, 11, www.ecologyand society.org/vol15/iss2/art11/.

Tubiello, F.N. and G. Fischer, 2007: Reducing climate change impacts on agriculture: global and regional effects of mitigation, 2000-2080. *Technological Forecasting and Social Change*, **74(7)**, 1030-1056.

Turner, B.L. II, R.E. Kasperson, P.A. Matson, J.J. McCarthy, R.W. Corell, L. Christensen, N. Eckley, J.X. Kasperson, A. Luers, M.L. Martello, C. Polsky, A. Pulsipher, and A. Schiller, 2003a: A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Sciences of the United States of America*, **100(14)**, 8074-8079.

Turner, B.L. II, P.A. Matson, J.J. McCarthy, R.W. Corell, L. Christensen, N. Eckley, G.K. Hovelsrud-Broda, J.X. Kasperson, R.E. Kasperson, A. Luers, M.L. Martello, S. Mathiesen, R. Naylor, C. Polsky, A. Pulsipher, A. Schiller, H. Selin, and N. Tyler, 2003b: Illustrating the coupled human-environment system for vulnerability analysis: three case studies. *Proceedings of the National Academy of Sciences of the United States of America*, **100(14)**, 8080-8085.

Twigg, J., 2001: *Sustainable Livelihoods and Vulnerability to Disasters*. Benfield Greig Hazard Research Centre, Disaster Management Working Paper 2/2001, Prepared by the Benfield Greig Hazard Research Centre for the Disaster Mitigation Institute (DMI), London, UK, 18 pp., www.eird.org/cd/on-better-terms/docs/Twigg-Sustainable-livelihoods-and-vulnerability-to-disasters.pdf.

UNDP, 2007: *Human Development Report 2007/2008. Fighting Climate Change: Human Solidarity in a Divided World.* United Nations Development Programme (UNDP), Palgrave Macmillan, Houndmills, UK and New York, NY, USA, 399 pp.

UNDRO, 1980: *Natural Disasters and Vulnerability Analysis.* Report of Expert Group Meeting 9-12 July 1979, Office of the United Nations Disaster Relief Co-ordinator (UNDRO), Geneva, Switzerland, 49 pp.

UNEP, 2007: *Global Environment Outlook 4.* United Nations Environment Programme, Nairobi, Kenya, 540 pp.

UNISDR, 2004: *Living with Risk: A Global Review of Disaster Reduction Initiatives.* Vol. 1, United Nations Office for Disaster Risk Reduction (UNISDR), Geneva, Switzerland, 430 pp.

UNISDR, 2009: *Reducing Disaster Risk through Science: Issues and Actions.* Full Report of the Scientific and Technical Committee 2009, United Nations International Strategy for Disaster Reduction (UNISDR), Geneva, Switzerland, 23 pp.

UNISDR, 2011: *Global Assessment Report on Disaster Risk Reduction.* United Nations Office for Disaster Reduction (UNISDR), Geneva, Switzerland, 178 pp.

UNISDR, 2013: *Global Assessment Report on Disaster Risk Reduction 2013*. United Nations Office for Disaster Reduction (UNISDR), Geneva, Switzerland, pp. 288.

Urban, N.M. and K. Keller, 2010: Probabilistic hindcasts and projections of the coupled climate, carbon cycle and Atlantic meridional overturning circulation system: a Bayesian fusion of century-scale observations with a simple model. *Tellus A*, **62(5)**, 737-750.

US DOE and BLM, 2012: *Final Programmatic Environmental Impact Statement (PEIS) for Solar Energy Development in Six Southwestern States.* FES 12-24 • DOE/EIS-0403, Prepared by the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), and The U.S. Department of the Interior (DOI), U.S. Bureau of Land Management, with assistance from Argonne National Laboratory, Washington, DC, USA, solareis.anl.gov/Documents/fpeis/index.cfm.

USDA, 2013: *Table 5. Corn Supply, Disappearance, and Share of Total Corn used for Ethanol.* U.S. Department of Agriculture (USDA) Economic Research Service (ERS), U.S. Bioenergy Statistics, Washington, DC, USA, 8 pp., www.ers.usda.gov/data-products/us-bioenergy-statistics.aspx#.Ux-g9_ldXTo.

van Nes, E.H. and M. Scheffer, 2005: Implications of spatial heterogeneity for catastrophic regime shifts in ecosystems. *Ecology*, **86**, 1797-1807.

van Sluis, E. and M. van Aalst, 2006: Climate change and disaster risk in urban environments. *Humanitarian Exchange Magazine*, **(35)**, 20-23.

van Vliet, J., M. van den Berg, M. Schaeffer, D.P. van Vuuren, M. den Elzen, A.F. Hof, A.M. Beltran, and M. Meinshausen, 2012: Copenhagen Accord pledges imply higher costs for staying below 2°C warming. *Climatic Change*, **113**, 551-561.

van Vuuren, D.P., E. Bellevrat, A. Kitous, and M. Isaac, 2010: Bio-energy use and low stabilization scenarios. *The Energy Journal*, **31(SI 1)**, 192-222.

van Vuuren, D.P., E. Stehfest, M.G. den Elzen, T. Kram, J. van Vliet, S. Deetman, M. Isaac, K. Klein Goldewijk, A. Hof, and A. Mendoza Beltran, 2011: RCP2. 6: exploring the possibility to keep global mean temperature increase below 2°C. *Climatic Change*, **109(1)**, 95-116.

van Vuuren, D.P., M.T. Kok, B. Girod, P.L. Lucas, and B. de Vries, 2012: Scenarios in global environmental assessments: key characteristics and lessons for future use. *Global Environmental Change*, **22(4)**, 884-885.

Villagrán de León, J.C., 2006: *Vulnerability: A Conceptual and Methodological Review.* SOURCE Publication Series of UNU-EHS, No. 4, United Nations University Institute for Environment and Human Security (UNU-EHS), Bonn, Germany, 64 pp.

Vrij, A., J. Van der Steen, and L. Koppelaar, 1994: Aggression of police officers as a function of temperature: an experiment with the Fire Arms Training System. *Journal of Community & Applied Social Psychology*, **4(5)**, 365-370.

Wada, Y., D. Wisser, S. Eisner, M. Flörke, D. Gerten, I. Haddeland, N. Hanasaki, Y. Masaki, F.T. Portmann, T. Stacke, Z. Tessler, and J. Schewe, 2013: Multimodel projections and uncertainties of irrigation water demand under climate change. *Geophysical Research Letters*, **40(17)**, 4626-4632.

Waldhoff, S. and A. Fawcett, 2011: Can developed economies combat dangerous anthropogenic climate change without near-term reductions from developing economies? *Climatic Change*, **107(3)**, 635-641.

Walker, B. and D. Salt, 2006: *Resilience Thinking: Sustaining Ecosystems and People in a Changing World.* Island Press, Washington, DC, USA, 192 pp.

Wallander, S., R. Claassen, and C. Nickerson, 2011: *The Ethanol Decade: An Expansion of U.S. Corn Production, 2000-09, EIB-79.* U.S. Department of Agriculture, Economic Research Service, 16 pp., http://www.ers.usda.gov/ersDownloadHandler.ashx?file=/media/121204/eib79.pdf.

Wang, J., S.G.S.A. Rothausen, D. Conway, L. Zhang, W. Xiong, I.P. Holman, and Y. Li, 2012: China's water-energy nexus: greenhouse-gas emissions from groundwater use for agriculture. *Environmental Research Letters*, **7(1)**, 014035, doi:10.1088/1748-9326/7/1/014035.

Wang, S., L. Hong, and X. Chen, 2012: Vulnerability analysis of interdependent infrastructure systems: a methodological framework. *Physica A: Statistical Mechanics and its Applications*, **391(11)**, 3323-3335.

Ward, P.J., M.A. Marfai, F. Yulianto, D.R. Hizbaron, and J.C.J.H. Aerts, 2011: Coastal inundation and damage exposure estimation: a case study for Jakarta. *Natural Hazards*, **56(3)**, 899-916.

Wardle, D.A., R.D. Bardgett, R.M. Callaway, and W.H. Van der Putten, 2011: Terrestrial ecosystem responses to species gains and losses. *Science*, **332(6035)**, 1273-1277.

Warner, K., 2010: Global environmental change and migration: governance challenges. *Global Environmental Change*, **20(3)**, 402-413.

Warner, K., K. van der Geest, S. Kreft, S. Huq, S. Harmeling, K. Kusters and A. de Sherbinin, 2012: *Evidence from the Frontlines of Cimate Change: Loss and Damage to Communities despite Coping and Adaptation.* Loss and Damage in Vulnerable Countries Initiative, UNU Policy Report 9, United Nations University Institute for Environment and Human Security (UNU-EHS), Bonn, Germany, 86 pp.

Warren, R., 2011: The role of interactions in a world implementing adaptation and mitigation solutions to climate change. *Philosophical Transactions of the Royal Society A*, **369(1934)**, 217-241.

Warren, R., C. Hope, M. Mastrandrea, R.S.J. Tol, W.N. Adger, and I. Lorenzoni, 2006: *Spotlighting the Impacts Functions in Integrated Assessments.* Research Report Prepared for the Stern Review on the Economics of Climate Change, Working Paper 91, Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, UK, 216 pp.

Warren, R., S. de la Nava Santos, N.W. Arnell, M. Bane, T. Barker, C. Barton, R. Ford, H.-M. Füssel, R.K.S. Hankin, R. Klein, C. Linstead, J. Kohler, T.D. Mitchell, T.J. Osborn, H. Pan, S.C.B. Raper, G. Riley, H.J. Schellnhüber, S. Winne, and D. Anderson, 2008: Development and illustrative outputs of the Community Integrated Assessment System (CIAS), a multi-institutional modular integrated assessment approach for modelling climate change. *Environmental Modelling & Software*, **23(5)**, 592-610.

Warren, R., J. Price, A. Fischlin, S. de la Nava Santos, and G. Midgley, 2011: Increasing impacts of climate change upon ecosystems with increasing global mean temperature rise. *Climatic Change*, **106(2)**, 141-177.

Warren, R., J. VanDerWal, J. Price, J. Welbergen, I. Atkinson, J. Ramirez-Villegas, T. Osborn, A. Jarvis, L. Shoo, and S. Williams, 2013a: Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. *Nature Climate Change*, **3**, 678-682.

Warren, R., J. Lowe, N. Arnell, C. Hope, P. Berry, S. Brown, A. Gambhir, S. Gosling, R. Nicholls, and J. O'Hanley, 2013b: The AVOID Programme's new simulations of the global benefits of stringent climate change mitigation. *Climatic Change*, **120(1-2)**, 55-70.

Watkiss, P. and A. Hunt, 2012: Projection of economic impacts of climate change in sectors of Europe based on bottom up analysis: human health. *Climatic Change*, **112(1)**, 101-126.

Wayne, P., S. Foster, J. Connolly, F. Bazzaz, and P. Epstein, 2002: Production of allergenic pollen by ragweed (*Ambrosia artemisiifolia* L.) is increased in CO_2-enriched atmospheres. *Annals of Allergy, Asthma & Immunology*, **88(3)**, 279-282.

Webber, B.L. and J.K. Scott, 2012: Rapid global change: implications for defining natives and aliens. *Global Ecology and Biogeography*, **21(3)**, 305-311.

Weber, E.U., 2006: Experience-based and description-based perceptions of long-term risk: why global warming does not scare us (yet). *Climatic Change*, **77(1)**, 103-120.

Weber, E.U., 2010: What shapes perceptions of climate change? *Wiley Interdisciplinary Reviews: Climate Change*, **1(3)**, 332-342.

Webster, M.D., 2008: Incorporating path-dependency into decision analytic methods: an application to global climate change policy. *Decision Analysis*, **5(2)**, 60-75.

Weitzman, M.L., 2010: What is the "damages function" for global warming – and what difference might it make? *Climate Change Economics*, **1(1)**, 57-69.

Welle, T., J. Birkmann, J. Rhyner, M. Witting, and J. Wolfertz, 2012: WorldRiskIndex 2012: concept, updating and results. In: *World Risk Report 2012* [Brodbeck, N. (ed.)]. Alliance Development Works, Berlin, Germany, pp. 11-26.

Wieser, H., R. Manderscheid, M. Erbs, and H. Weigel, 2008: Effects of elevated atmospheric CO_2 concentrations on the quantitative protein composition of wheat grain. *Journal of Agricultural and Food Chemistry*, **56(15)**, 6531-6535.

Wiltshire, A.J., G. Kay, J.L. Gornall, and R.A. Betts, 2013: The impact of climate, CO_2 and population on regional food and water resources in the 2050s. *Sustainability*, **5(5)**, 2129-2151.

Wise, M., K. Calvin, A. Thomson, L. Clarke, B. Bond-Lamberty, R. Sands, S.J. Smith, A. Janetos, and J. Edmonds, 2009: Implications of limiting CO_2 concentrations for land use and energy. *Science*, **324(5931)**, 1183-1186.

Wisner, B., 1998: Marginality and vulnerability: why the homeless of Tokyo don't 'count' in disaster preparations. *Applied Geography*, **18(1)**, 25-33.

Wisner, B., 2006: *Let Our Children Teach Us! A Review of the Role of Education and Knowledge in Disaster Risk Reduction*. ISDR System Thematic Cluster / Platform on Knowledge and Education, Books *for* Change, Bangalore, India, 135 pp.

Wisner, B., P. Blaikie, T. Cannon, and I. Davis, 2004: *At Risk: Natural Hazards, People's Vulnerability and Disasters.* Routledge, Abingdon, UK and New York, NY, USA, 471 pp.

World Bank, 2010: *World Development Report 2010: Development and Climate Change*. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 439 pp.

World Bank, 2011: *World Development Report 2011: Conflict, Security, and Development.* The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 416 pp.

World Bank, 2012: *Poverty Data.* The World Bank Group, Washington, DC, USA, data.worldbank.org/topic/poverty.

World Commission on Dams, 2000: *Dams and Development: A New Framework for Decision-Making.* Earthscan, London, UK, 356 pp.

Wright, S.J., H.C. Muller-Landau, and J. Schipper, 2009: The future of tropical species on a warmer planet. *Conservation Biology*, **23(6)**, 1418-1426.

Yang, Y., J. Bae, J. Kim, and S. Suh, 2012: Replacing gasoline with corn ethanol results in significant environmental problem-shifting. *Environmental Science and Technology*, **46(7)**, 3671-3678.

Yohe, G.W. and D. Tirpak, 2008: A research agenda to improve economic estimates of the benefits of climate change policies. *Integrated Assessment*, **8(1)**, 1-17.

Yohe, G. and R.S.J. Tol, 2002: Indicators for social and economic coping capacity – moving toward a working definition of adaptive capacity. *Global Environmental Change*, **12(1)**, 25-40.

Zickfeld, K. and T. Bruckner, 2008: Reducing the risk of Atlantic thermohaline circulation collapse: sensitivity analysis of emissions corridors. *Climatic Change*, **91(3)**, 291-315.

Zickfeld, K., A. Levermann, M.G. Morgan, T. Kuhlbrodt, S. Rahmstorf, and D.W. Keith, 2007: Expert judgements on the response of the Atlantic meridional overturning circulation to climate change. *Climatic Change*, **82(3)**, 235-265.

Ziervogel, G. and P.J. Ericksen, 2010: Adapting to climate change to sustain food security. *Wiley Interdisciplinary Reviews: Climate Change*, **1(4)**, 525-540.

Zilberman, D., G. Hochman, and D. Rajagopal, 2011: Indirect land use change: a second-best solution to a first-class problem. *Journal of Agrobiotechnology Management and Economics*, **13(4)**, 11, 382-390.

Zinck, R.D., M. Pascual, and V. Grimm, 2011: Understanding shifts in wildfire regimes as emergent threshold phenomena. *The American Naturalist*, **178(6)**, E149-E161, doi:10.1086/662675.

Ziska, L.H. and P.J. Beggs, 2012: Anthropogenic climate change and allergen exposure: the role of plant biology. *Journal of Allergy and Clinical Immunology*, **129(1)**, 27-32.

Ziska, L.H. and F.A. Caulfield, 2000: Rising CO_2 and pollen production of common ragweed (*Ambrosia artemisiifolia* L.), a known allergy-inducing species: implications for public health. *Functional Plant Biology*, **27(10)**, 893-898.

Ziska, L.H., D.E. Gebhard, D.A. Frenz, S. Faulkner, B.D. Singer, and J.G. Straka, 2003: Cities as harbingers of climate change: common ragweed, urbanization, and public health. *Journal of Allergy and Clinical Immunology*, **111(2)**, 290-295.

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Climate-Resilient Pathways: Adaptation, Mitigation, and Sustainable Development

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This chapter should be cited as:
Denton, F., T.J. Wilbanks, A.C. Abeysinghe, I. Burton, Q. Gao, M.C. Lemos, T. Masui, K.L. O'Brien, and K. Warner, 2014: Climate-resilient pathways: adaptation, mitigation, and sustainable development. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1101-1131.

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Executive Summary

Climate change calls for new approaches to sustainable development that take into account complex interactions between climate and social and ecological systems. Climate-resilient pathways are development trajectories that combine adaptation and mitigation to realize the goal of sustainable development. They can be seen as iterative, continually evolving processes for managing change within complex systems.

This chapter integrates a variety of complex concepts in assessing climate-resilient pathways. It takes sustainable development as the ultimate goal, and considers mitigation as a way to keep climate change moderate rather than extreme. Adaptation is considered a response strategy to anticipate and cope with impacts that cannot be (or are not) avoided under different scenarios of climate change. In most cases, sustainable development will also involve capacities for implementing and sustaining appropriate risk management. Responses may differ from situation to situation, calling for a multiscale perspective that takes the socioeconomic, cultural, biophysical, and institutional context into account. Nonetheless, most situations share at least one fundamental characteristic: threats to sustainable development are greater if climate change is substantial rather than moderate. Similarly, opportunities for sustainable development are greater if climate change is moderate rather than substantial.

Although findings from this chapter are based on a high level of consensus in source materials and in the expert communities, the amount of supporting evidence is relatively limited because so many aspects of sustainable development and climate change mitigation and adaptation have yet to be experienced and studied empirically. The task of this chapter is to suggest options to be considered for decision making, both now and in the future, as elements of the evolving processes for a variety of locations and scales. This chapter's findings are as follows.

Climate change poses a moderate threat to current sustainable development and a severe threat to future sustainable development (*high confidence*; *medium evidence*, *high agreement*). Some climate-related impacts on development are already being observed (e.g., changes in agriculture, increases in coastal vulnerability). Added to other stresses such as poverty, inequality, or diseases, the effects of climate change will make sustainable development objectives such as food and livelihood security, poverty reduction, health, and access to clean water more difficult to achieve for many locations, systems, and affected populations. {20.2.1}

Climate-resilient pathways include strategies, choices, and actions that reduce climate change and its impacts. They also include actions to ensure that effective risk management and adaptation can be implemented and sustained (*high confidence*; *medium evidence*, *high agreement*). Adaptation and mitigation have the potential to both contribute to and impede sustainable development, and sustainable development strategies and choices have the potential to both contribute to and impede climate change responses. Adaptation and mitigation are needed, working together to reduce risks of disruptions from climate change. These actions, however, may introduce trade-offs between adaptation and mitigation, and between economic goals and environmental goals. In some cases, for example, adaptation may increase greenhouse gas emissions (e.g., increased fossil-based air conditioning in response to higher temperatures) and in some cases mitigation may impede adaptation (e.g., reduced energy availability in countries with growing populations). In many cases, strategies for climate change responses and strategies for sustainable development are highly interactive. {20.3-4}

The integration of adaptation and mitigation responses can in some cases generate mutual benefits, as well as introduce co-benefits with development policies (*high confidence*; *medium evidence*, *medium agreement*). In many cases, reducing the risk of climate change can enhance capacities for management of other risks. Opportunities to take advantage of positive synergies may decrease with time, particularly if the limits to climate change adaptation are exceeded. {20.2.1, 20.3.2-3, 20.5.1}

Prospects for climate-resilient pathways are related fundamentally to what the world accomplishes with climate change mitigation, but both mitigation and adaptation are essential for climate change risk management at all scales (*high confidence*; *medium evidence*, *high agreement*). As the magnitude of climate change increases and the consequences become increasingly significant to many areas, systems, and populations, the challenges to sustainable development increase. Beyond some magnitudes and rates of climate change, the impacts on most systems would be great enough that sustainable development may no longer be possible for many systems and locations. At the local scale, governments, businesses, communities, and individuals in many developing regions have limited capacities to mitigate climate

change because they contribute very little to global emissions. They may also have relatively limited capacities to adapt for reasons of income, education, health, security, political power, or access to technology. At all scales, however, mitigation and adaptation actions are fundamental for effective implementation of climate risk management and reduction. {20.2.2, 20.3, 20.6.1}

To promote sustainable development within the context of climate change, climate-resilient pathways may involve significant transformations (*high confidence*; *medium evidence*, *high agreement*). Transformations in economic, social, technological, and political decisions and actions can enable climate-resilient pathways. Although transformations may be reactive, forced, or induced by random factors, they may also be deliberately created through social and political processes. Whether in relation to mitigation, adaptation, or sustainable development, it is possible to identify enabling conditions that support transformations. Nonetheless there are legitimate concerns about the equity and ethical dimensions of transformation. {20.5}

Strategies and actions can be pursued now that will move toward climate-resilient pathways while at the same time helping to improve livelihoods, social and economic well-being, and responsible environmental management (*high confidence*; *medium evidence*, *high agreement*). Transformations to sustainability benefit from iterative learning, deliberative processes, and innovation. {20.4}

Delayed action in the present may reduce options for climate-resilient pathways in the future (*high confidence*; *medium evidence*, *high agreement*). In some parts of the world, current failures to address effects of emerging climate stressors are already eroding the basis for sustainable development and offsetting previous gains. Opportunities to design and implement solutions that promote climate-resilient pathways exist now, and they can capture development co-benefits of improving livelihoods and social and economic well-being. Current actions will emphasize climate risk management strategies informed by growing evidence, knowledge, and experience. {20.6.2}

More research about the relationship between mitigation, adaptation, and sustainable development is needed, as well as research on the relationship between incremental changes and more significant transformations for sustainable development (*high confidence*; *robust evidence*, *high agreement*). Priorities for research include improving understandings of benefits, costs, synergies, trade-offs, and limitations of major mitigation and adaptation options, along with implications for equitable development to facilitate decision making about climate-resilient pathways (*high confidence*; *robust evidence*, *high agreement*).

20.1. Introduction

Following summaries of *what we know* about climate change impacts, vulnerabilities, and prospects for adaptation (Chapter 18) and reasons for concern (Chapter 19), this chapter summarizes what is currently known about options regarding *what to do* in responding to these risks and concerns.

In terms of "what to do" to address climate change and threats to development now and in the future, the chapter identifies and discusses climate-resilient pathways. Climate-resilient pathways are defined in this chapter as development trajectories that combine adaptation and mitigation with effective institutions to realize the goal of sustainable development. They are seen as iterative, continually evolving processes for managing change within complex socio-ecological systems; taking necessary steps to reduce vulnerabilities to climate change impacts in the context of development needs and resources, building capacity to increase the options available for vulnerability reduction and coping with unexpected threats; monitoring the effectiveness of vulnerability reduction efforts; and revising risk reduction responses on the basis of continuous learning. As such, climate-resilient pathways include two main categories of responses:

- Actions to reduce human-induced climate change and its impacts, including both mitigation and adaptation toward achieving sustainable development
- Actions to ensure that effective institutions, strategies, and choices for risk management will be identified, implemented, and sustained as an integrated part of achieving sustainable development.

In many cases, each of the two categories of responses has the potential to benefit the other as well, offering potentials for win-win kinds of integration, although mechanisms and institutions are needed to address cases where the two elements have negative effects on each other and to ensure that positive synergies are realized. Because climate change challenges are significant for many areas, systems, and populations, climate-resilient pathways will generally require transformations—beyond incremental approaches—in order to ensure sustainable development (see Sections 20.2.3.1, 20.6.2; for related language employed by the UNFCCC, see Box 20-1).

Incremental responses to climate change address immediate and anticipated threats based on current practices, management approaches, or technical strategies. These may involve developing energy-efficient vehicles to mitigate climate change, or building higher dykes to adapt to sea level rise. Incremental responses are often referred to as business-as-usual approaches, as they do not challenge or disrupt existing systems (Kates et al., 2012). Transformative responses, in contrast, involve innovations that contribute to systemic changes by challenging some of the assumptions that underlie business-as-usual approaches (O'Brien, 2012). Transformational adaptations, for example, change the nature, composition, and/or location of threatened systems (Smit and Wandel, 2006; Stringer et al., 2009; National Research Council, 2010a; Pelling, 2010; IPCC, 2012). Importantly, transformations of the systems, structures, relations, and behaviors that contribute to climate change and social vulnerability may also be necessary to reduce risks to sustainable development, as discussed in Section 20.5.2 (see also WGIII AR5 Chapter 6 on Assessing Transformation Pathways).

Frequently Asked Questions

FAQ 20.1 | What is a climate-resilient pathway for development?

A climate-resilient pathway for development is a continuing process for managing changes in the climate and other driving forces affecting development, combining flexibility, innovativeness, and participative problem solving with effectiveness in mitigating and adapting to climate change. If effects of climate change are relatively severe, this process is likely to require considerations of transformational changes in threatened systems if development is to be sustained without major disruptions.

Conceptual understandings of sustainable development have developed considerably, particularly over the past 2 decades, as the short- and long-term implications of climate change and extreme events have become better understood, although empirical evidence of progress with sustainable development is often elusive. The discussion of sustainable development in the IPCC process has evolved since the First Assessment Report (FAR), which focused on the technology and cost-effectiveness of mitigation activities, and the Second Assessment Report (SAR), which included issues related to equity and to environmental and social considerations. The Third Assessment Report (TAR) further broadened the treatment of sustainable development by addressing issues related to global sustainability, and the Fourth Assessment (AR4) included chapters on sustainable development in both Working Group II and III reports, with a focus on both climate-first and development-first literatures.

This chapter recognizes climate change as a threat to sustainable development. The chapter emphasizes that, as a result, transformational changes are very likely to be required for climate-resilient pathways—both transformational adaptations and transformations of social processes that make such transformational adaptations feasible. The chapter integrates a variety of complex issues in assessing climate-resilient pathways in a variety of regions at a variety of scales: sustainable development as the ultimate aim, mitigation as the way to keep climate change impacts moderate rather than extreme, adaptation as a response strategy the way to keep climate change impacts moderate rather than extreme or to cope with impacts that cannot be (or are not) avoided, and development pathways as contexts that shape choices and actions. It stresses needs and opportunities to make progress toward climate-resilient pathways now, rather than postponing responses to an indefinite future.

The chapter is organized in six parts: climate change as a threat to sustainable development, by assessing links between sustainable development and climate change as well as defining climate-resilient pathways (Section 20.2); contributions to resilience through climate change responses (Section 20.3); contributions to resilience through

Box 20-1 | Goals for Climate-Resilient Pathways

Climate-resilient pathways are development trajectories of combined mitigation and adaptation to realize the goal of sustainable development that help avoid "dangerous anthropogenic interference with the climate system" as specified in Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC).

Article 2 of the UNFCCC outlines its ultimate objective as the "*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system* … in order to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner." Article 3.4 of the Convention recognizes that "*Parties have a right to and should promote sustainable development.*" A number of recent decisions by the Conference of the Parties (COP) to the UNFCCC has attempted to recognize the scientific view that the increase in global temperature should be below 2°C and encourage long-term cooperative action to combat climate change. The Decisions agreed in Cancun at COP-16 recognize "… *deep cuts in global greenhouse gas emissions are required according to science*, and as documented in the Fourth Assessment Report of the IPCC, with a view to reducing global greenhouse gas emissions so as to hold the increase in global average temperature below 2°C above preindustrial levels … consistent with science … [and] also recognizes the need to consider … strengthening the long-term global goal on the basis of the best available scientific knowledge." The preamble of the Cancun Decisions highlights the central importance of the link between climate change and employment and "*Realizes that addressing climate change requires a paradigm shift towards building a low-carbon society that offers substantial opportunities and ensures continued high growth and sustainable development, based on innovative technologies and more sustainable production and consumption and lifestyles, while ensuring a just transition of the workforce that creates decent work and quality jobs*" (UNFCCC, 2011, Decision 1/CP.16). The 2011 COP, in a decision known as the Durban Platform, increases the strength of the language in the Decision 1/CP.17 to conclude, "… *climate change represents an urgent and potentially irreversible threat to human societies and the planet* and thus requires to be urgently addressed … with a view to accelerating the reduction of global greenhouse gas emissions...." This decision was followed by the decisions adopted in Doha at the 18th Conference of the Parties that noted with grave concern the significant gap between the aggregate effect of Parties' mitigation pledges in terms of global annual emissions of greenhouse gases by 2020 and aggregate emission pathways consistent with having a likely chance of holding the increase in global average temperature below 2°C or 1.5°C above preindustrial levels. As such, the current UNFCCC negotiations have identified +2°C or 1.5°C as the desirable target upper limit,implicitly equating this with "dangerous" in Article 2.

sustainable development strategies and choices (Section 20.4); determinants of resilience in the face of serious threats (Section 20.5); challenges in moving toward climate-resilient pathways (Section 20.6); and priority gaps in knowledge (Section 20.7).

Several of the terms that are central to this chapter have been defined earlier in the WGII contribution to the Fifth Assessment Report, including climate, adaptation, and mitigation. In addition, by "resilient" we mean a system's ability to anticipate, reduce, accommodate, and recover from disruptions in a timely, efficient, and fair manner (IPCC, 2012). For literatures on "sustainable development," see Section 20.2. A summary definition is development that meets the needs of the present without compromising the ability of future generations to meet their own needs (see Glossary). It achieves continuing improvements in human well-being and ensures a sustainable relationship with a physical environment that is already under stress, reconciling trade-offs among economic, environmental, and other social goals through institutional approaches that are equitable and participative in order themselves to be sustainable.

Frequently Asked Questions

FAQ 20.2 | What do you mean by "transformational changes"?

Transformational change is a fundamental change in a system, its nature, and/or its location that can occur in human institutions, technological and biological systems, and elsewhere. It most often happens in responding to significantly disruptive events or concerns about them. For climate-resilient pathways for development, transformations in social processes may be required to get voluntary social agreement to undertake transformational adaptations that avoid serious disruptions of sustainable development.

20.2. Climate Change as a Threat to Sustainable Development

Climate-resilient pathways bring together (1) sustainable development as the larger context for societies, regions, nations, and the global community with (2) climate change effects as threats to (and possibly opportunities for) sustainable development and (3) responses to reduce any effects that would undermine future development and even offset already achieved gains. Resilience is defined in this report as the ability of a social, ecological, or socio-ecological system and its components to anticipate, reduce, accommodate, or recover from the effects of a hazardous event or trend in a timely and efficient manner (see Glossary). Climate resilience refers to the outcomes of evolutionary processes of managing change in order to reduce disruptions and enhance opportunities. Considering alternative climate-resilient pathways cannot be separated from levels of climate change. Overall, most climate change scientists, decision makers, and stakeholders agree that (1) there is a level of climate change that is low enough that climate resilience for most systems could be achieved without enormous efforts and widespread transformational adaptation; (2) there is a level of climate change that is high enough that climate resilience cannot be expected to cope with severe impacts on most systems (e.g., Rockstrom et al., 2009); and (3) between those two levels the challenges to climate resilience grow as the level of climate change rises. Scientists do not, however, agree on what magnitude of climate change (e.g., average global warming) defines each of the two levels. Some experts support the view (Box 20-1 and Section 20.3.1) that any level above 2°C would mean impacts that are incompatible with sustainable development (Metz et al., 2002). The Summary for Policymakers of the WGII AR4 indicated that there is an approximate threshold between 2.5°C and 3°C of warming, above which impact concerns are severe but below which concerns are less severe (IPCC, 2007b, Figure SPM.2; see also Smith et al., 2009). Other scientists are unconvinced that system sensitivities to climate parameters such as temperature increase are understood well enough to support any specific warming threshold (e.g., National Research Council, 2010c), and some scientists and policymakers are unconvinced that adaptive management and adaptive response capacities are well enough understood to support determinations of limits to adaptation and resilience (Chapter 16). Most experts in all three groups, however, agree that prospects for climate-resilient development pathways are related fundamentally to what the world accomplishes with climate change mitigation (e.g., New et al., 2012).

20.2.1. Links between Sustainable Development and Climate Change

20.2.1.1. Objectives of Sustainable Development

Different actors have used the concept of sustainable development to pursue a variety of objectives in policy and practice worldwide, with the common denominator of delivering improved human well-being while sustaining environmental services (Sen, 1999; Morgan and Farsides, 2009; Von Bernard and Gorbaran, 2010). "Sustainable development" is a concept rooted in concerns about balance in the relationships between society and nature (e.g., Brown, 1981). The Brundtland Report (WCED, 1987, p. 43) defines the idea as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." It contains within it two key concepts of "needs": in particular the essential needs of the world's poorest, to which overriding priority should be given; and the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs (Rao, 2000). It stresses that equitable economic development is key to addressing environmental problems both in developing and developed regions in ways that are sustainable for the long term (Halsnaes et al., 2008; Lafferty and Meadowcroft, 2010).

Historically, policy and science have subsequently influenced the development of the concept. Concerns about declining environmental quality, and increasing population growth, coupled with increasing rates of consumption (energy, natural resources, input-intensive living standards), motivated changes in some countries, related for example to:

- Water and air quality standards
- Management of hazardous materials
- Changes in regulation (although some literature says that current institutional controls and linkages are counterproductive (Barker, 2008; O'Hara, 2009; Scrieciu et al., 2013))
- Agricultural and industrial practices
- Water and solid waste management
- A movement toward greater efficiency in resource use including recycling
- An emphasis on energy efficiency, progressing toward renewable energy as an alternative to non-renewable fossil fuel resources (Frey and Linke, 2002).

In this context, global discourse and practice have helped to establish principles and aspirational plans. Examples include Agenda 21, which is a comprehensive plan of action adopted at the 1992 Earth Summit by more than 178 governments (Sitarz, 1994) and the 2012 "Rio+20" conference, which issued a statement urging countries to renew their commitment to sustainable development. Improved understandings of the short- and long-term implications of climate change and extreme events (IPCC FAR, SAR, TAR, AR4, *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX)) have influenced conceptualizations of sustainable development and related objectives such as poverty reduction, health, livelihood and food security, and other aspects of human welfare related to the idea of "climate-resilient development." These discussions occurred against an emerging understanding of "rights to development" (e.g., UNFCCC Article 2), juxtaposed with the lack of consensus about justifiable patterns of consumption and a recognition that development processes have altered global environmental systems, including climates (Crutzen and Stoermer, 2000; IPCC, 2007a, 2012; Oliver-Smith et al., 2012). However, in practice some national authorities interpret sustainable development as pursuing current economic development (Beg et al., 2002; Swart et al., 2003; Arndt et al., 2012; Yohe, 2012), as many countries aspire to carbon-intensive development models akin to the systems in place in most industrialized countries—from food production, trade, and transport to household consumption (Grist, 2008; Brown, 2011; Sanwal, 2012).

In contrast, to many observers, carbon-intensive development models in industrialized and developing countries appear broadly inconsistent

with objectives such as poverty reduction, improving human health, and securing food and livelihoods associated with the idea of sustainable development (Ehrenfeld, 2008; Grist, 2008; Marston, 2012; see also Victor and Rosenbluth, 2007; Victor, 2008) and with efforts to define and establish "safe operating spaces" for humanity (Röckstrom et al., 2009; Preston et al., 2013). While diverse interpretations of the concept are used, the literature suggests that many indicators of human welfare are already being compromised to some degree and at different scales by climate-related stressors (see Section 20.2.1.2).

One way that sustainable development pathways can contribute to climate resilience is by pursuing consumption patterns that ensure social and economic development while reducing use of natural resources and maintaining ecosystem services. It is possible that the desired objectives of consumption might be met in ways that require fewer resources and produce fewer emissions (Kates, 2000b; see also Leiserowitz et al., 2005). Ideas about equity and values play a role in sustainable development and how policy makers perceive trade-offs in aims to improve human well-being. In many cases, growth in consumption that raises human well-being (such as food and health services), especially among populations with incomes rising from low levels, is a catalyst for economic and social development (Clark et al., 2008; Deaton, 2008). In contrast, for populations already at high consumption levels, increasing material consumption does not necessarily translate into higher well-being (Easterlin, 1974, 2001; Adger, 2010; see also WGIII AR5 Chapter 4). This observation is reflected in research on subjective human happiness, satisfaction, and material comfort (Huesemann, 2006; Dolan and White, 2007; Fleurbaey, 2009; Cafaro, 2010; DeLeire and Kalil, 2010).

Box 20-2 | Key Reasons for Concern about Climate Change Effects on Sustainable Development

Chapter 19 identifies a number of "Key Risks, Key Vulnerabilities, and Reasons for Concern" (see especially Section 19.6.3 and Table 19-4). Emergent risks from climate change related to sustainable development include losses of ecosystem services, challenges to land and water management, effects on human health, particular risks of severe harm and loss in certain vulnerable areas, increasing prices of food commodities on the global market, consequences for migration flows at particular times and places, increasing risks of flooding, risks of food insecurity, systemic risks to infrastructures from extreme events, loss of biodiversity, and risks for rural livelihoods. These risks differ according to the magnitude of climate change and both regional and socioeconomic differences in vulnerability. Some unique and threatened systems are at risk at current temperatures, with risks increasing at even relatively small increases in global mean temperature. Risks grow if the magnitude of warming increases.

20.2.1.2. Risks and Threats Posed by Climate Change, Interacting with Other Factors and Driving Forces

As the implications of climate change and their extent become better understood (Chapter 18) and as particular reasons for concern have begun to come into focus (Chapter 19), climate change has been increasingly seen as an issue for sustainable development—with the potential either to aid or impede its successful implementation (e.g., Halsnaes et al., 2008; Munasinghe, 2010).

The links between sustainable development and climate adaptation and mitigation are cross-cutting and complex. First, the impacts of climate change, and ill-designed responses to these impacts, may derail current sustainable development policy and potentially offset already achieved gains. These impacts are expected to affect numerous sectors such as agriculture, forestry, and energy; threaten coastal zones and other vulnerable areas; and pose critical challenges to governance and political systems (World Bank, 2010, pp. 39-69; Adger et al., 2011; IPCC, 2012; see also Box 20-2 and Chapters 18, 19). Examples include poverty and livelihoods (Chapter 13), food security (Chapter 7), human security (Chapter 12), rural and urban areas (Chapters 8, 9), and economic sectors (Chapters 10, 17). For instance, effects of climate change on key ecological resources and systems can jeopardize sustainable development in systems closely dependent on natural capital. Moreover, although impacts will affect both developed and developing regions, the latter are considered especially problematic owing to lower adaptive capacity (World Bank, 2010, Chapter 13; Lemos et al., 2013). Second, mitigation has the potential to keep these threats at a moderate rather than extreme level, and adaptation will enhance the ability of different systems to cope with the remaining impacts, therefore modulating negative effects on sustainable development (IPCC, 2007a).

Third, many of the conditions that define vulnerability to climate impacts and the ability to mitigate and adapt to them are firmly rooted in development processes (e.g., structural deficits and available assets and entitlements) (Brooks et al., 2005; Lemos et al., 2013; see also Section 15.2.1). Indeed, climate change will act as a threat multiplier and will create new poor in low-income countries and middle- to high-income countries (Chapter 13). Fourth, sustainable development intersects with many of the drivers of climate change, especially regarding energy production and consumption and the ability to mitigate emissions (IPCC, 2011; see also Chapter 9). Fifth, because several of the desirable characteristics of climate responses and sustainable development may overlap (e.g., implementation of no-regrets options, equitable distribution of resources, increased adaptive capacity and livelihood capitals, functioning ecosystems and maintained biodiversity), systems that prioritize sustainable development may be better at designing and implementing successful mitigation and adaptation (Forsyth, 2007; Brown, 2011).

Finally, climate mitigation and adaptation, if planned and integrated well, have the potential to create opportunities to foster sustainable development (see Section 20.3.3). Under the threat of climate change,

sustainable development depends on changes in social awareness and values that lead to innovative actions and practices, including increased attention to both disaster risk management and climate change adaptation in anticipation of (and in response to) changes in climate extremes (IPCC, 2012). Understanding how to enhance positive feedbacks between mitigation, adaptation, and sustainable development (e.g., win-win and triple-win interventions) while minimizing potential trade-offs between them (see Section 20.3.3) is an essential part of planning for and pursuing climate-resilient pathways. In the following paragraphs, we discuss these links in light of empirical research and specific examples (Box 20-2; also see discussions of Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) in Chapter 1). While some of the links described above have been contemplated in the scholarly literature, there remain considerable gaps in our knowledge base to inform climate-resilient pathways.

Frequently Asked Questions

FAQ 20.3 | Why are climate-resilient pathways needed for sustainable development?

Sustainable development requires managing many threats and risks, including climate change. Because climate change is a growing threat to development, sustainability will be more difficult to achieve for many locations, systems, and populations unless development pathways are pursued that are resilient to effects of climate change.

The relationship between climatic change and development policy has often been theorized as essentially twofold. On the one hand, climate change will affect development policy as needs to respond to negative, and perhaps positive, impacts arise (Burton et al., 2002; Halsnaes and Verhagen, 2007; IPCC, 2007a; Schipper, 2007). On the other hand, development policy critically shapes carbon emission paths, the ability to develop sustainable adaptation and mitigation options, and to build overall adaptive capacity (Bizikova et al., 2007; Metz and Kok, 2008; Garg et al., 2009; Lemos et al., 2013). Because of the recognized relationship between development and climate change drivers and responses, some authors have called for a "political economy of climate change" that takes into consideration ideas, power, and resources at different scales from the local to the global (e.g., Tanner and Allouche, 2011).

Enhancing resilience to respond to effects of climate change includes adopting good development practices that are consonant with building sustainable livelihoods and, in some cases, challenging current models of development (Boyd et al., 2008; McSweeny and Coomes, 2011). Moreover, promoting development pathways that are both equitable and sustainable is also a key to addressing climate change (Wilbanks, 2003; Nelson et al., 2007). In this sense, integrating sustainable development and overall climate change policy can be all the more relevant if "cross-linkages between poverty, the use of natural capital and environmental degradation" are recognized (Veeman and Politylo, 2003, p. 317; see also Matthew and Hammill, 2009). Especially in less developed regions, the relationship between vulnerability to climate impacts and development is often very close and mutually dependent, as such realities as low per capita income and inequitable distribution of resources; lack of education, health care, and safety; and weak institutions and unequal power relations fundamentally shape sensitivity, exposure, and adaptive capacity to climate impact (Kates, 2000a; Adger et al., 2003; Garg et al., 2009; McSweeny and Coomes, 2011; Lemos et al., 2013). In these regions, reducing risks that affect resource-dependent communities is increasingly viewed as a necessary but insufficient way to tackle the myriad problems associated with climate change impacts (Jerneck and Olsson, 2008). Building the capacity of individuals, communities, and governance systems to adapt to climate impacts is both a function of dealing with developmental deficits (e.g., poverty alleviation, reducing risks related to famine and food insecurity, enabling/implementing public health and mass education and literacy programs) and of improving risk management (e.g., alert systems, disaster relief, crop insurance, seasonal climate forecasts, risk insurance) (Mirza, 2003; Schipper and Pelling, 2006; IPCC, 2012; Warner et al., 2012a; see also Chapters 12, 13). Hence, it is important to understand not only the relative importance of different kinds of interventions (climate and non-climate) in building adaptive capacity but also the potential positive and negative synergies between them (Lemos et al., 2013).

While research increasingly highlights the intersection between vulnerability, adaptive capacity, and developmental structural deficits (see Chapter 13 for a detailed discussion), there is also growing recognition that the intractability of many of these problems may inhibit the development of climate-resilient pathways. For example, in northeast Brazil, the fact that local traditional politics relied on patron-client relationships with drought-affected households to maintain power suggests that there was little incentive for policies that dramatically decreased their level of vulnerability (Tompkins et al., 2008). Omolo (2010) argues that in northwestern Kenya, in pastoralist societies of Turkana, in spite of increasing numbers of women-headed households, participation of women in key decisions such as investment, resource allocation, and planning on where to move or settle in the aftermath of drought and floods is still quite low. A serious concern is that our inability to readily address these kinds of structural problems may limit options for future generations of marginalized social groups to be active agents of a climate-resilient future. In this sense, it is critical to understand how existing path-dependent trajectories (e.g., socio-technical, behavioral, institutional) that form the contextual basis for climate change action at different scales (Burch, 2010) may inhibit (or help) the realization of future climate-resilient pathways.

A number of studies recognize that not every possible response to climate change is consistent with sustainable development, as some strategies and actions may have negative impacts on the well-being of others and of future generations (Gardiner et al., 2010; Eriksen et al., 2011; see also Section 19.3.2.5). For example, some mitigation interventions such as the subsidization of the ethanol industry in the USA might compromise long-term resilience through both undesirable ecological effects (e.g., loss of crop diversity, soil erosion, and aquifer depletion) and social effects (e.g., reduction of flexibility for alternative fuel development, potential for food insecurity; Adger et al., 2011). Likewise, in central Vietnam some responses to climate change impact, such as building

dams to prevent flooding and saltwater intrusion and to generate power, threaten the livelihood of poor communities. First, the relocation of communities and the inundation of forestland to build dams limit households' access to land and forest products. Second, a government focus on irrigated rice agriculture can reduce poor households' ability to diversify their income portfolio, decreasing their long-term adaptive capacity (Beckman, 2011). Indeed, the consequences of responses to climate change, whether related to mitigation or adaptation, can negatively influence future vulnerability, unless there is awareness of and response to these interactions (Eriksen et al., 2011). Here, the role of values in responding to climate change becomes important from a variety of perspectives, including intergenerational, particularly when those currently in positions of power and authority assume that their prioritized values will be shared by future generations (O'Brien, 2009; Eriksen et al., 2011). Acknowledging the importance of intergenerational equity, it has been argued that participatory processes and "deliberative democracy" can include the concerns, values, and perceptions of a wide range of stakeholders, raising some of the ethical impacts attached to climate-related risks (Backstrand, 2003; see also Deere-Birebeck, 2009). Such an approach could have a bearing on the way risks are assessed and addressed at the science-policy interface, with significant implications for sustainable development. For example, research by Wolf et al. (2009) on climate change responses in western Canada shows that individual quests to minimize their environmental impact and sense of responsibility (normatively defined as ecological citizenship) play an important role in the identification and implementation of sustainable responses to water scarcity. In contrast, inequitable distribution of power among those affected by climate impact can suppress innovative decisions about the future by limiting participation in designing solutions. In light of the complex interactions among climate change responses and sustainable development, there is a need for more holistic responses that place human well-being and security at the forefront, while building on existing strengths and capacities (Tompkins and Adger, 2004; O'Brien et al., 2010). This entails integrating multiple objectives and policy goals in order to promote responses to climate change that contribute to resilience and that are sustainable as social and policy conditions change (Meadowcroft, 2000; Tompkins and Adger, 2004; Pintér et al., 2011).

A reality in many countries may be that development in its many forms (economic, human, and sustainable) can enhance the capacity to adapt (Lemos et al., 2013), while at the same time adding to greenhouse gas (GHG) emissions. Yet, the World Development Report 2010 suggests that climate change responses have the potential to contribute to sustainable development as, for example, in the case of financial assistance with transition to low-carbon growth paths (World Bank, 2010) or in the case of mitigation policies that could increase income and/or enhance the quality of growth in vulnerable groups such as Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+). And while vulnerable sectors such as agriculture give us particular reasons for concern (see Box 20-2), they may offer opportunities in some instances to reduce climate-related risks and threats by integrating both adaptation and mitigation strategies as a lever for reducing poverty and promoting climate-resilient pathways. Particularly necessary is addressing institutional and social capacities for responding to both climate change impacts and mitigation responses. For example, Chhatre and Agrawal (2009) show that climate change mitigation can benefit livelihoods if ownership of forest commons is transferred to local communities.

Some interventions related to climate change responses aim to combine goals of sustainable development, climate change adaptation, and climate change mitigation into "win-win" or "triple-win" approaches that highlight overlaps between these goals. Examples include mechanisms such as the Clean Development Mechanism (CDM) and Joint Implementation (JI) (e.g., Millar et al., 2007), which may seek to offset carbon emissions, build adaptive capacities of local communities, and provide sustainable development dividends despite mixed results in terms of accomplishing these goals in practice (Corbera and Brown, 2008). Specifically in the case of the CDM, robust empirical research shows overwhelming negative results in win-win terms—while the goal of offsetting carbon emissions has fared better, generating sustainable development dividend has been difficult. For example, after examining 16 existing CDM projects around the world, Sutter and Parreno (2007) found that whereas they could meet 72% of their emissions reduction goals, fewer than 1% might actually contribute significantly to sustainable development in the host country. Furthermore, their research suggests that there might be an actual trade-off between the goals of efficient generation of certified emissions reduction (CERs) and the broader generation of the sustainable development dividend (see also Winkelman and Moore, 2011). Even when relatively successful, triple-win interventions may result in unequal distribution of benefits across mitigation, adaptation, and sustainable development (Bryan et al., 2013). Because relationships among the three goals can lead to both positive and negative consequences, it is important to unravel conditions that lead to desirable outcomes (Chhartre and Agrawal, 2009) (see Section 20.3.3). Moreover, the fact that currently available institutional arrangements that attempt to combine mitigation and sustainable development (such as CDM) are not achieving win-win goals indicates the need for rapidly developing means for evaluating, changing, and improving current policy instruments and mechanisms (Dovers and Hezri, 2010).

Given these connections, there is growing consensus in the literature about a need to integrate development and climate policies; however, the means to achieve this integration differ and are not without controversy (see, e.g., Seballos and Kreft, 2011). An approach often described in the literature is mainstreaming, where governments incorporate climate-related concerns into existing policy (Dovers and Hezri, 2010). A major factor constraining the "mainstreaming" of climate adaptation into development is the disconnect between access to globally available adaptation funds and developing countries' own development agendas (Hardee and Mutunga, 2009; Seballos and Kreft, 2011). This disconnect can potentially inhibit the development of robust local organizations and institutions that effectively integrate or mainstream climate change considerations into development priorities. In particular, research focusing on the National Adaptation Programmes of Action (NAPAs) and the Strategic Programmes for Climate Resilience (SPCRs), designed to support least developed countries to mainstream adaptation, shows that lack of coordination between government sectors, lack of technical capacity, and discrepancies between long-term development goals and short-term adaptation interventions still constrain mainstreaming efforts (Saito, 2013; see also Section 15.2). Even where climate-related initiatives and programs are reasonably well

coordinated, bureaucratic complexities can cause communities to be overlooked (Chukwumerije and Schroeder, 2009). For example, in Mexico, despite the governmental discourse supporting climate change policy, actual implementation of mitigation and adaptation actions have been constrained by lack of resources and institutional coordination and limited societal involvement (Sosa-Rodriguez, 2013). Other factors—such as lack of financial and human resources, unclear distribution of costs and benefits, fragmented management, mismatches in scale of governance and implementation, lack and unequal distribution of climate information, lack of institutional memory, and trade-offs with other priorities—may also limit the smooth mainstreaming of climate adaptation action into development (Eakin and Lemos, 2006; Bizikova et al., 2007; Agrawala and van Aalst, 2008; Kok et al., 2008; Metz and Kok, 2008, Sietz et al., 2011). Finally, empirical evidence suggests that the relationship between development variables and climate change responses can be a mixture of positives and negatives, if development variables are not managed well (Garg et al., 2009). For example, in a study of the relationship between malaria incidence, development, and climate variables in India, Garg et al. (2009) found that while some development interventions such as building irrigation canals and dams can, in some cases, increase the incidence of malaria and water-borne diseases (when they exacerbate potential breeding grounds for malarial parasites), others such as higher per capita income can reduce negative health impacts of climate change significantly—although the distribution of benefits can differ between types of interventions (also see Campbell-Landrum and Woodruff, 2006). Understanding how development variables intersect with climate responses is especially important because governments and other actors rarely make decisions in isolation; rather, they respond to multiple stressors both in rural and urban environments (Eakin, 2005; Agrawal, 2010; Wilbanks and Kates, 2010; Lemos et al., 2013). Moreover, some evidence suggests that, in practice, decision makers (from heads of households to policy makers) often do not place climate change at the top of their priority list of critical issues to address (Garg et al., 2007; Kok et al., 2008), although this situation seems to be changing. Moreover, the increasing importance of climatic change in shaping social and governmental policy agendas has resulted in a growing number of examples of specific interventions to respond to climate change, both in developed and developing regions (Ayers and Huq, 2009; Burch, 2010; Bierbaum et al., 2013; for examples of adaptation planning see Chapter 15, especially Section 15.2, and Chapter 14, especially Section 14.3).

20.2.2. Climate-Resilient Pathways

20.2.2.1. Framing Climate-Resilient Pathways

Climate-resilient pathways integrate current and evolving understandings of climate change consequences and conventional and alternative development pathways to meet the goals of sustainable development (see WGIII AR5 Chapter 4). They can be seen as development trajectories that include both mitigation and adaptation, as well as effective development institutions. Climate-resilient pathways represent iterative processes for managing change within complex systems, where unintended consequences are common owing to feedbacks, teleconnections, cross-scale linkages, thresholds, and nonlinear effects (Folke et al., 2002; Scheffer et al., 2009; Lenton, 2011a). Climate-resilient pathways recognize that increasing atmospheric concentrations of GHGs can lead to impacts that have long-term implications for sustainable development. The observed and projected impacts of climate change on poverty and livelihoods, food and water security, health, and human security are well documented in this report (see Chapters 11, 12, 13).

The pursuit of climate-resilient pathways involves identifying vulnerabilities to climate change impacts; assessing opportunities for reducing risks; and taking actions that are consistent with the goals of sustainable development. These actions may involve a combination of incremental and transformative responses that take into account (1) current and anticipated changes in both climate averages and extremes; (2) the dynamic development context that influences social vulnerability, risk perception, conflict resolution, and resilience; and (3) recognition of human agency and capacity to influence the future. This last point is significant, as humans have the capacity to manage risk and to decrease vulnerability through both mitigation and adaptation, as well as through choices of development goals and strategies (IPCC, 2012).

Climate-resilient pathways call for decisions and actions that take into account both short- and long-term time horizons. In the short term, society will have to adapt to changes in the climate that are linked to past emissions, and both incremental and transformative adaptation may thus be significant. Mitigation responses taken in the short term will have a strong influence on climate-resilient pathways for sustainable development in the future, shaping needs for transformative adaptation over a long time horizon. Considering the potential for nonlinear impacts associated with increasing global temperatures, the threats to sustainable development are likely to become greater over time (Wilbanks et al., 2007; Stafford et al., 2010; see also Chapter 12). Discussions of climate-resilient pathways thus cannot be separated from levels of climate change.

20.2.2.2. Elements of Climate-Resilient Pathways

If climate change continues on its current path toward relatively significant impacts (National Research Council, 2010b), climate-resilient pathways will become increasingly challenging, requiring explicit attention to responses in virtually all regions, sectors, and systems to avoid disruptions of development processes. Climate-resilient pathways include two overarching attributes: (1) actions to reduce climate change and its impacts, including both mitigation and adaptation, and (2) actions to ensure that effective risk management institutions, strategies, and choices can be identified, implemented, and sustained as an integrated part of development processes (Edenhofer et al., 2012). Box 20-3 draws on material throughout the chapter to list a number of attributes of climate-resilient pathways categorized into awareness and capacity, resources, and practices. Each of the items is amenable to strategy development in appropriate national, regional, and local contexts. For example, in many cases effective response to extreme events can benefit both from iterative problem-solving and bottom-up engagement in risk management, and from human development to enhance capacities for risk management and adaptive behavior (Tompkins et al., 2008). Folke (2006) characterizes resilience as a process of innovation and development. Pathways should therefore be continuously moving toward a more adapted and less vulnerable state; in some instances,

Box 20-3 | Selected Elements of Climate-Resilient Pathways

Awareness and capacity

- A high level of social awareness of climate change risks
- A demonstrated commitment to contribute appropriately to reducing net greenhouse gas emissions, integrated with national development strategies
- Institutional change for more effective resource management through collective action
- Human capital development to improve risk management and adaptive capacities
- Leadership for sustainability that effectively responds to complex challenges

Resources

- Access to scientific and technological expertise and options for problem solving, including effective mechanisms for providing climate information, services, and standards
- Access to financing for appropriate climate change response strategies and actions
- Information linkages in order to learn from experiences of others with mitigation and adaptation

Practices

- Continuing development and evaluation of institutionalized vulnerability assessments and risk management strategy development, and refinement based on emerging information and experience
- Monitoring of emerging climate change impacts and contingency planning for responding to them, including possible needs for transformational responses
- Policy, regulatory, and legal frameworks that encourage and support distributed voluntary actions for climate change risk management
- Effective programs to assist the most vulnerable populations and systems in coping with impacts of climate change

there may be stages of slow development followed by periods where progress increases speed. Further, the nonlinearity, variability, and uncertainty of climate impacts necessitate a system that allows for the flexibility to adapt to unexpected and even extreme events (Holling, 1973). This is especially true in light of political, economic, or resource constraints, where pathways at the local level will need to be not only flexible but also practical and feasible in both the short term and long term. One of the most challenging aspects of climate-resilient pathways is that they exist in distinctive local contexts, where they are shaped by external linkages that connect them across geographic scales and time. For example, resilience cannot be achieved in a few privileged places if it is not achieved in other connected places, because instabilities in adversely impacted situations will spill over to other situations through such effects as resource supply constraints, conflict, migration, or disease transmission (Wilbanks, 2009; IPCC, 2012, Chapter 7).

Climate-resilient pathways are in fact a process, not an outcome (Manyena, 2006), involving both incremental and transformational changes. The pathways therefore need to be built on a foundation of constantly advancing knowledge, where information is adjusted based on changing scientific knowledge on climate parameters and altering social, economic, and natural resource situations (Berkes, 2007). While some measures will be reactive, the main elements of a pathway are intentional and proactive: anticipating future change and developing appropriate plans and responses. Although payoffs from specific long-term pathways may be unknown, strategies and actions can be pursued now that will contribute significantly to moving toward climate-resilient pathways while helping improve human livelihoods, social and economic well-being, and responsible environmental management (Section 20.6.2).

20.3. Contributions to Resilience through Climate Change Responses

Climate change responses include mitigation, adaptation, and integrated mitigation and adaptation strategies. Related to these responses but generally considered a separate response issue is "geoengineering" (see Box 20-4).

20.3.1. Mitigation

In IPCC's assessment reports, mitigation is the subject of WGIII, to which readers are referred for comprehensive information about options and strategies for reducing GHG emissions and increasing GHG uptakes by the Earth system. For this chapter, the issue is how climate change

Box 20-4 | Considering Geoengineering Responses

If climate change mitigation is not sufficiently successful, policymakers may be faced with demands to find further ways to reduce climate change and its effects.

Such options include intentional large-scale interventions in the Earth system either to reduce the amount of absorbed solar energy in the climate system or to increase the uptake of carbon dioxide (CO_2) from the atmosphere (see Glossary). An example of the former is to inject sulfates into the stratosphere. Examples of the latter include facilities to scrub CO_2 from the air and chemical interventions to increase uptakes by oceans, soil, or biomass (UK Royal Society, 2009; WGIII AR5 Chapter 6; WGI AR5 Chapters 6, 7; see also Chapter 19).

Discussions of geoengineering have only recently become an active area of discourse in science, despite a longer history of efforts to modify climate (Schneider, 1996, 2008; Keith, 2000; Crutzen, 2006). Many of the possible options are known to be technically feasible, but their costs, effectiveness, and side effects are exceedingly poorly understood (National Research Council, 2010b; Goes et al., 2011; MacCracken, 2011; Vaughan and Lenten, 2011). For example, some interventions in the atmosphere might not be unacceptably expensive in terms of direct costs, but they might affect the behavior of such Earth system processes as the Asian monsoons (Robock et al., 2008; Brovkin et al., 2009). Some interventions to increase carbon uptakes, such as scrubbing CO_2 from the Earth's atmosphere, might be socially acceptable but economically very expensive. Moreover, it is possible that optimism about geoengineering options might invite complacency regarding mitigation efforts.

In any case, implications for sustainable development are largely unknown. Even though some views have been expressed that geoengineering is needed now to avoid irreversible impact such as the loss of biodiversity (while many governments have not begun to consider it at all), several countries consider it a research priority rather than a current decision-making option (National Research Council, 2010b). The challenge is to understand what geoengineering options would do to moderate global climate change and also to understand what their ancillary effects and risks might be. This would allow policymakers in the future to respond if severe disruptions appear and, as a result, there is a need to consider rather dramatic technology alternatives. Some observers propose that research efforts should include limited experiments with geoengineering options, but agreement has not been reached about criteria for determining what experiments are appropriate or ethical (Chapter 19.5.4; WGIII AR5 Chapter 3.3.7; Blackstock and Long, 2010; Gardiner, 2010).

mitigation relates to sustainable development, which was addressed by WGII AR4 Chapter 12 (IPCC, 2007a) and is also the focus of WGIII AR5 Chapter 4, including attention to equity issues.

In general terms, mitigation is recognized to be important for sustainable development in two ways (Riahi, 2000). First, it reduces the rate and magnitude of climate change, which reduces climate-related stresses on sustainable development, including effects of extreme weather and climate events (Washington et al., 2009; Lenton, 2011b; IPCC, 2012; see also Section 20.2; Box 20-1). But recent observations of the rate of increase in global carbon dioxide emissions (e.g., Peters et al., 2013) suggest that the challenge of stabilizing concentrations is growing (for further information about international accords, national pledges and inventory reports, and continuing negotiations, along with summaries of current and projected progress with mitigation, see WGIII AR5).

Second, trajectories for technological and institutional change to reduce net GHG emissions interact with development pathways. In some cases, national pledges to achieve mitigation targets (e.g., Figure 20-1) may be congruent with sustainable development in urban settings, such as green growth strategies that reduce local and regional air pollution, enhancing prospects for multilevel governance and integrated management of resources, and encouraging broader participation in development processes (Lebel, 2005; Seto et al., 2010). In other cases, such effects as higher energy prices associated with transitions from fossil fuels to renewable energy sources have the potential to have adverse effects on local and regional economic and social development (IPCC, 2011, Chapter 9).

The challenge for climate-resilient pathways is to identify and implement mixes of technological and governance options that reduce net carbon emissions and at the same time support sustainable economic and social growth in a context where rising demands for economic and social development need to be combined with technology transitions without disrupting the development process. For example, strategies such as increasing carbon uptakes and decreasing carbon losses in the soil

through better agricultural management practices—which can reduce net emissions—can improve soil water storage capacity. Practices such as conservation tillage can also increase water retention in drought conditions and help to sequester carbon in soils (Halsnaes et al., 2008). In many cases, however, this challenge remains very difficult to meet.

Mitigation and development also interact in a third way in that different groups and countries' abilities to implement mitigation critically depends on their "mitigative capacity" (Yohe, 2001): their "ability to reduce anthropogenic greenhouse gas emissions or enhance natural sinks" and the "skills, competencies, fitness, and proficiencies that a country has attained which can contribute to GHG emissions mitigation" (Winkler et al., 2007). Here, many of the determinants of mitigative capacity are fundamentally shaped by different countries' levels of development, including their current level of emissions; their stock of human, financial, and technological capital, such as the ability to pay for mitigation; the magnitude and cost of available abatement opportunities; the regulatory effectiveness and market rules; the education and skills base; the suite of mitigation technologies available; the ability to absorb new technologies; and the level of infrastructure development (Box 20-4).

20.3.2. Adaptation

Adaptation is the subject of four chapters of this WGII AR5 (Chapters 14 to 17), to which readers are referred for comprehensive descriptions of concepts, options, strategies, and examples of adaptation practices. For this section, we focus on the intersection between adaptation and sustainable development. Overall, climate adaptation and sustainable development are linked in several ways: first, many of the determinants of adaptive capacity to respond to climate impact and indicators of sustainable development overlap; second, adaptive capacity building may critically contribute to the well-being of both social and ecological systems; and third, building adaptive capacity within a sustainable development framework may require transformational changes (Dovers and Hezri, 2010; Kates et al., 2012; Lemos et al., 2013).

Around the globe, the ability of communities and individuals to respond to climate change is predicated on a number of capacities (e.g., human capital, information and technology, material resources and infrastructure, organizational and social capital, political capital, wealth and financial capital, institutions and entitlements) that typically overlap with indicators of development (Smit and Pilifozofa, 2001; Yohe and Tol, 2002; Eakin and Lemos, 2006). However, building these capacities both in developed and less developed regions has implications for sustainable development because it might increase the consumption of materials and create potential negative effects on ecosystems (e.g., building of new infrastructure and increasing consumption). In terms of governance, climate change adaptation and sustainable development share many characteristics (e.g., issues of spatial and temporal scales, uncertainty, poorly defined jurisdictions; Dovers and Hezri, 2010), and designing and implementing successful interventions require different kinds of capacities, including political and administrative structures (Eakin and Lemos, 2006; Wilbanks et al., 2007). Building adaptive capacity may critically contribute to the improvement of the well-being of both social and ecological systems by bettering livelihoods and reducing pressure

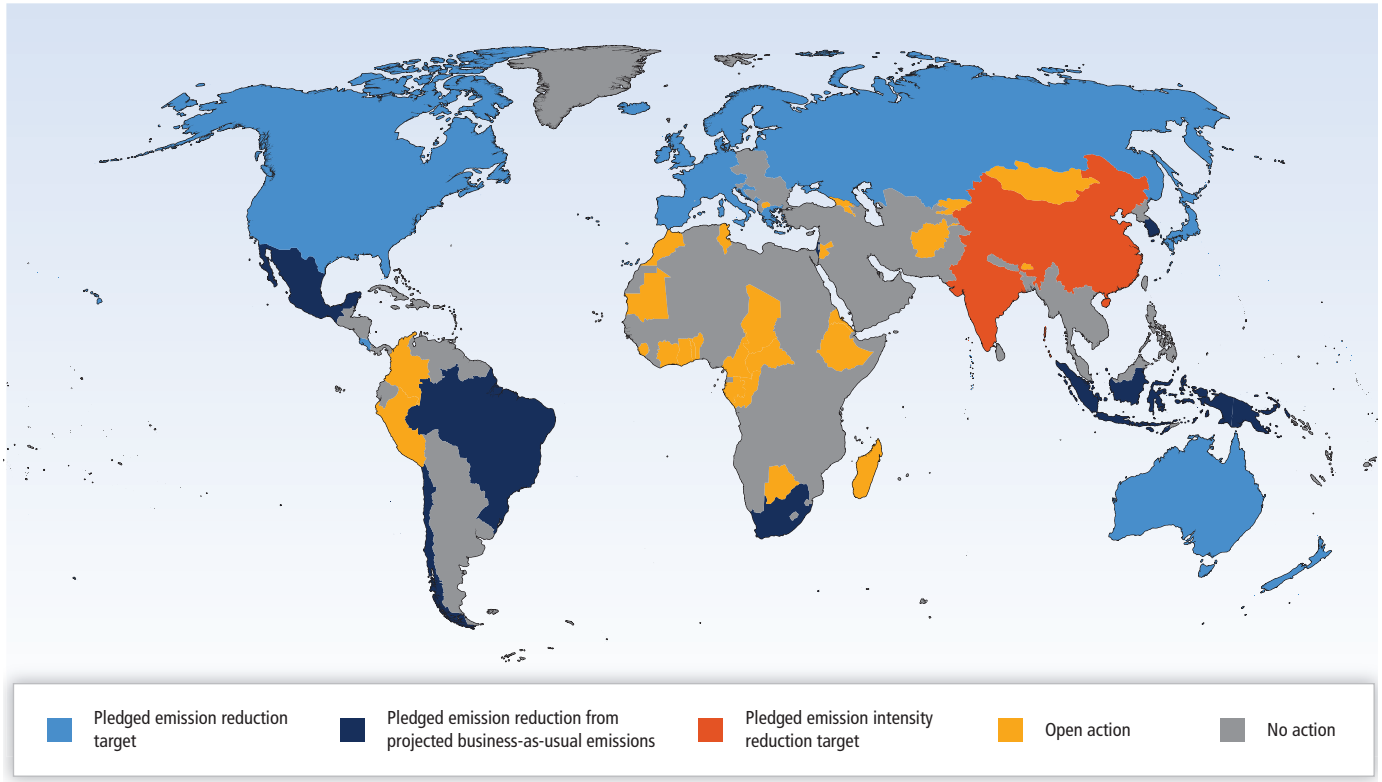

Figure 20-1 | Pledges by Annex 1 and Annex 2 countries in response to the Copenhagen Accord (see http://unfccc.int/meetings/copenhagen_dec_2009/items/5264.php, http://unfccc.int/meetings/cop_15/copenhagen_accord/items5265.php). Refer to Table SM21-1 for groupings of countries and territories of the world of relevance for international climate change policy making.

Box 20-5 | Case Studies from China

Water-saving irrigation has enhanced climate change adaptation capacity, improved ecosystem services, and promoted regional sustainable development in China:

- *Water-saving irrigation measures in cropland adaptation to climate change*. Water-saving irrigation is one effective measure to deal with the water scarcity and food security issues caused by climate change (Hanjra and Qureshi, 2010; Tejero et al., 2011). Given an increase in non-agricultural water consumption, China's agriculture could be faced with a severe shortage of water resources (Xiong et al., 2010). Through water-saving irrigation practices, water saved from 2007 to 2009 added up to a total of 61.82–129.66 10^9 m^3, which accounted for 5.6–11.8% of the national total water consumption; total energy saved was equal to 9.59–20.85 Mt of standard coal; and total CO_2 emissions were reduced by 21.83–47.48 Mt of CO_2. Therefore, water saving irrigation has had a positive effect in dealing with climate change and sustainable development (Zou et al., 2012).

Table 20-1 | Water and energy savings and CO_2 emission reductions from water-saving irrigation measures in cropland.

	2007	2008	2009
Water saved (10^9 m^3)	19.37–40.86	19.86–41.55	22.58–47.25
Energy saved (Mt of standard coal)	2.92–6.39	3.08–6.72	3.58–7.73
CO_2 emission reduction (Mt of CO_2)	6.66–14.58	7.02–15.31	8.15–17.59

- *Water-saving irrigation measures in alpine grassland for adapting to climate change*. In recent years, the rise in precipitation and temperature has led to the melting of glaciers and expansion to inland high mountain lakes, contributing to alpine grassland degradation in northern Tibet (Gao et al., 2010). Among many grassland protection measures, alpine grassland water-saving irrigation measures could be effective in redistributing and making full use of increased precipitation and lake water in the dry period, which would reduce the negative effects of climate change and make full use of favorable conditions (Editorial Board of National Climate Change Assessment, 2011; Gao et al., 2012). A 3-year demonstration of alpine grassland water-saving irrigation measures showed that alpine grassland primary productivity nearly doubled while the number of plant species increased from 19 to 29, helping to protect and restore the alpine grassland ecosystem and ecosystem services and to promote regional socioeconomic sustainable development in Northern Tibet (Gao et al., 2012).

on the environment, especially in less developed regions (see Section 20.4.3). Regarding social systems, it is important to consider not only the factors that enable the building of different capacities (e.g., institutions and governance) but also how to guarantee that those who need it the most have access to them (Nelson et al., 2007; Gupta et al., 2010). It is also vital to understand how different capacities influence each other, positively and negatively (Lemos et al., 2013), and how they may affect the long-term resilience of social-ecological systems (Adger et al., 2011; Box 20-5). Indeed, adaptation can be important in reducing stresses on development processes, especially in vulnerable areas where it can help to promote and support sustainable development. For example, where adaptation planning stimulates participatory social processes, including equity and legitimacy, as well as discussions regarding different adaptation options, it can encourage communities to think more clearly about broader sustainable development goals and pathways (National Research Council, 2010a).

Given recent trends in GHG emissions and projections of climate futures that suggest impacts of climate change will be serious and widespread (e.g., Auerswald et al., 2011; Smith et al., 2011), adaptation may require considering transformational changes, in which potentially impacted systems move to fundamentally new patterns, dynamics, and/or locations (Schipper, 2007; Kates et al., 2012; Marshall et al., 2012; Park et al., 2012). Desirable adaptation strategies may vary according to specific kinds of climate change threat, location, impacted system, the geographical scale of attention, and the time frame of strategic risk management planning (Thomalla et al., 2006; Heltberg et al., 2009; National Research Council, 2010a). Transformational adaptation policy at different scales needs to take into consideration the goals of sustainable development, both by fostering positive synergies and by avoiding negative feedbacks between them. This is especially important because some adaptation options might lead to inequitable and unsustainable outcomes, and some adaptations at one scale may negatively affect vulnerability in another (Thomas and Twyman, 2005; Eriksen et al., 2011; Eriksen and Brown, 2011; see also Sections 20.3.3, 20.4.4 and Chapter 14 for a more detailed discussion). For example, in the USA, building adaptive capacity for water management through drought preparedness plans at one scale (the state level) may constrain the flexibility of managers at lower scales (community water systems) to respond successfully to drought (Engle, 2013).

Indeed, adaptation pathways can foster food and water security, human health, and air and water quality and natural resource management, while promoting gender equality and other desirable outcomes consistent with sustainable development goals. However, creating the conditions for the emergence of such outcomes will require better integration in the implementation of policies and programs at all scales. By selecting materials not harmful to the environment, promoting the conservation

of energy, water, and other resources, promoting reuse and recycling, minimizing waste generation, protecting habitat, and addressing needs of marginalized groups, adaptation can contribute to win-win and triple-win options that can support a diverse array of development goals (Bizikova et al., 2007; Seto et al., 2010; see also Sections 15.3.1, 20.3.3 and UNFCCC, 2011).

20.3.3. Integrating Climate Change Adaptation and Mitigation for Sustainable Risk Management

Because both adaptation and mitigation are parts of climate-resilient pathways, and because each benefits from progress with the other (e.g., Section 20.2), integrating the two kinds of climate change responses within the broader context of sustainable development has been suggested as an aspirational goal (Wilbanks et al., 2007; Bizikova et al., 2010), especially when policy attention and financial commitments to climate change responses must consider the pursuit of both adaptation and mitigation. In practice, however, mitigation and adaptation tend to involve different time frames, communities of interest, and decision-making responsibilities (IPCC, 2007a; Wilbanks et al., 2007).

Integration of climate change responses with development processes is a further aspirational goal. Recent research suggests that mitigation and adaptation are likely to be more effective when they are designed and implemented in the context of other interventions within the broader context of sustainability and resilience (Wilbanks and Kates, 2010; ADB and ADBI, 2012). Moreover, studies focusing on the intersection between sustainable development and climate policy point out that integration between the two is a desirable although complex path (Section 20.2.1.2; Beg et al., 2002; Robinson et al., 2006; Swart and Raes, 2007; Wilson and McDaniels, 2007; Halsnaes et al., 2008; Ayers and Huq, 2009). Wilson and McDaniels suggest three reasons to integrate across adaptation, mitigation, and sustainable development: (1) many dimensions of the *values* that are important for decision making are common to all three decision contexts; (2) impacts from any one of the three decision contexts may have important *consequences* for the others; and (3) the *choice among alternatives* in one context can be a means for achieving the underlying values important in the others.

A key factor in integrating climate change adaptation and mitigation into sustainable risk management is to understand the processes of decision making at different scales. The distribution of costs and benefits of mitigation and adaptation differ; for example, mitigation benefits are more global, adaptation benefits are often more localized, the research and policy discourses are often unrelated, and the constituencies and decision makers are often different (mitigation may involve powerful industrial stakeholders from the energy sector concentrated at higher levels of decision making, while adaptation may involve more dispersed stakeholders at the local level across sectors) (Wilbanks et al., 2007). To significantly reduce total global emissions, mitigation decisions must be taken either by major emitters, or by groups of countries. At the national and international level, direct responsibilities to curb the main drivers of global climate change are dispersed across countries (Banerjee, 2012). In contrast, adaptation often falls to practitioners where local responsibility is clearer, although it often depends on support from national and global scale (Tanner and Allouche, 2011).

In many cases, the challenge of fostering synergies while avoiding negative feedbacks often comes into focus in place-based discussions of climate change responses and development objectives such as localities and small regions (Dang et al., 2003; Wilbanks, 2003; Bulkeley and Schroeder, 2012). Globally, a particular hurdle is the practice of applying available mitigation resources only for reducing emissions beyond that which would have occurred without those resources ("*additionality*"), when access to resources for adaptation efforts should take into account the critical role of *co-benefits* in supporting development in other ways while at the same time reducing vulnerabilities to climate change impacts (National Research Council, 2010a; see also Section 20.4.1).

Choices in integrating adaptation and mitigation will vary according to the circumstances of each country and each locality (Wilbanks, 2003; De Boer et al., 2010). In highly vulnerable countries, adaptation may be seen as the highest priority because there are immediate benefits to be obtained by reducing vulnerabilities to current climate variability and extremes as well as future climate changes. In the case of developed countries, adaptation initiatives have often been seen as a lower priority because it is perceived that there is abundant adaptive capacity (Naess et al., 2005). Yet major losses and damages in some industrialized countries related to climatic variability and extremes challenge this perception (e.g., Hurricane Sandy, tornadoes, and drought in the USA in 2011 and 2012). Mitigation may be seen as more acute political question—involving well-organized stakeholders concerned about costs—in countries that contribute a large proportion of GHG emissions (e.g., National Research Council, 2011), and it may be seen as an investment opportunity for the domestic private sector.

As indicated above, one emerging strategy to integrate climate and development policies is the design of "win-win" and "triple-win" interventions that seek to achieve an appropriate mix of mitigation and adaptation within the context of sustainable development (Pyke et al., 2007; Swart and Raes, 2007). Swart and Raes suggest a number of factors that should be taken into consideration when evaluating combined adaptation and mitigation policy designs, including (1) avoiding trade-offs, when designing policies for mitigation or adaptation; (2) identifying synergies; (3) enhancing response capacity; (4) developing institutional links between adaptation and mitigation, for example, in national institutions and in international negotiations; and (5) mainstreaming adaptation and mitigation considerations into broader sustainable development policies. Box 20-5 provides a case study of an initiative in China that has been a winner for both climate change responses and regional sustainable development. The potential for climate-resilient pathways may already be limited, however, in part because of path dependency stemming from choices on mitigation, adaptation, and political interpretations and subsequent choices around "sustainable" development (Swart et al., 2003; Barker, 2008); and, in many cases, interventions have not delivered win-win results, which raises questions about the actual attainability of win-win strategies given legal, political, economic, and/or institutional obstacles (Warner et al., 2012b; see also Section 20.2.1.2).

In synthesizing evidence from a series of empirical articles focusing on the intersection between mitigation and adaptation (M&A), Wilbanks and Sathaye (2007) argue that M&A pathways might be alternatives in reducing costs, complementary to and reinforcing each other (e.g.,

improvements in building energy efficiency), or competitive and mutually contradictory (e.g., coastal protection vs. reductions in sea level rise). In Bangladesh, for example, waste-to-compost projects contribute to mitigation through reducing methane emissions; to adaptation through soil improvement in drought-prone areas; and to sustainable development through the preservation of ecosystem services (Ayers and Huq, 2009; also see Vergara et al., 2012, regarding possible development benefits of mitigation and adaptation in Latin America and the Caribbean). Land management and forestry activities contribute to ecosystem-based mitigation, for example, through the reduction of emissions from deforestation and forest degradation, and adaptation, for example, through the conservation of hydrological services provided to people facing water problems, as well as renewable energy (see several cases of ecosystem-based adaptation in Pramova et al., 2012). However, trade-offs are also possible, for example, if ecosystem management for mitigation purposes reduces the livelihood opportunities and the adaptive capacity of local people (Locatelli et al., 2011). The scale of these examples is often local, however, and longer term success of these pathways will depend on the broader context of mitigation and facilitation of adaptation options (Metz et al., 2002).

When integrating across the goal of finding climate-resilient pathways (and win-win solutions), decision makers often need to address issues of scale, along with trade-offs in values such as economic profitability versus stability of food and livelihood security (e.g., in agricultural policy), relationships between development ends and means, uncertainty and path dependencies, and institutional complexity (Tol, 2004; Klein et al., 2005; Wilson and McDaniels, 2007). They also need to consider the possibility of ancillary co-benefits, complementarities and potential contradictions, opportunity costs, and unknown negative and positive feedbacks (e.g., interactions among options and paybacks (Rosenzweig and Tubiello, 2007; Swart and Raes, 2007; Wilbanks and Sathaye, 2007; Kok et al., 2008; IPCC, 2007a, Chapter 18; National Research Council, 2010a)). Current research is examining trade-offs and complementarities between mitigation and adaptation in different sectors. In the energy sector, for instance, Kopytko and Perkins (2011) have examined to what extent the siting of nuclear power plants might constrain future adaptation to sea level rise. Others ask about such issues as adaptation implications of the production of biofuels (La Rovere et al., 2009); agriculture and water (Rosenzweig and Tubiello, 2007; Shah, 2009; Falloon and Betts, 2010; Rounsevell et al., 2010; Turner et al., 2010); conservation (Rounsevell et al., 2010; Turner et al., 2010); use of mitigation programs to finance adaptation (Hof et al., 2009); and the urban environment (Biesbroek et al., 2009; Hamin and Gurran, 2009; Roy, 2009; Romero-Lankao and Wilbanks, 2011; Viguié and Hallegatte, 2012).

20.4. Contributions to Resilience through Sustainable Development Strategies and Choices

Although climate change responses can contribute significantly to climate-resilient development pathways, some of the key elements of resilience lie in sustainable development implementation, which can make resilience either more or less achievable. Examples of ways that development strategies and choices can contribute to climate resilience include being capable of resolving trade-offs among economic and environmental goals (e.g., Bamuri and Opeschoor, 2007), ensuring effective institutions in developing, implementing, and sustaining resilient strategies, and enhancing the range of choices through innovation (e.g., Folke et al., 2002; Chuku, 2009; Hallegatte, 2009).

20.4.1. Resolving Trade-offs between Economic and Environmental Goals

Sustainable development pathways will be more climate resilient if they develop and utilize socioeconomic and institutional structures that are effective in resolving trade-offs among social, economic, and environmental goals—a central tenet of sustainable development (Section 20.2.1.1). As climate change poses risks to goals such as poverty reduction, food and livelihood security, human health, and economic prosperity (Chapter 19), societies face the task of defining how to manage these risks and what levels of risk without compromising what they value most and what defines their societies. The management of risk—and the weighting of various categories of risk—depends on social definitions of what consequences are acceptable, tolerable, or intolerable (Chapter 16).

There is a long-standing assumption that economic growth is in conflict with environmental management (Victor and Rosenbluth, 2007; Hueting, 2010). Much of this thinking can be traced back to Malthus and his assertions that population growth (and associated consumption) would expand at an increasing rate until the limits of the Earth's capacity were reached (Malthus, 1798). The very idea of sustainable development itself springs from a need to respond to such Malthusian ideas. The views expounded in the Brundtland Report, for example, are that development should not be unconstrained but should rather be modified into a "sustainable" form (WCED, 1987). Views about relationships between economic growth and environmental protection range widely from arguments that sustainable development is inconsistent with continued economic growth (e.g., Robinson, 2004) to arguments that economic growth and associated technological innovation can enhance options for environmental management (Lovins and Cohen, 2011). Relationships between affluence and environmental protection are complex, as poverty can lead to land degradation and affluence can afford support for nature preservation, while economic growth is built on levels of resource extraction and use that require significant changes in environments. Sustainable development cannot escape continuing tensions between economic growth and environmental management goals, where strongly held views across society often differ so fundamentally that conflict results unless social processes and institutional mechanisms are effective in resolving a host of trade-offs (Boyd et al., 2008), with both values and processes varying according to development context.

Examples of frameworks of thought often related to addressing trade-offs are multi-metric valuation and co-benefits (see also Ness et al., 2007, regarding tools for sustainability assessment; Bizikova et al., 2008, Appendix 1; Gulledge et al., 2010):

- *Multi-metric valuation*. In evaluating development pathways, there are often needs to combine a number of dimensions associated with different valuation metrics and information requirements, such as monetary measures of returns and non-monetary metrics of risk.

Fields ranging from aquatic ecology to risk assessment and financial management have developed tools for such complex valuations, including graphical mapping (e.g., Sheppard and Meitner, 2005; Rose, 2010; Moed and Plume, 2011; UNFCCC, 2011) and the construction of multi-metric indexes (e.g., Johnston et al., 2011). Multi-metric indicators have been widely studied and critiqued, and they are an active topic of research (e.g., Drouineau et al., 2012; Schoolmaster, 2013). A key challenge is weighting different valuations being combined quantitatively, which may be addressed in part by constructing multiple indices. More commonly in collective decision making, however, analytical-deliberative group processes are used to evaluate, weight, and combine different dimensions and metrics qualitatively (National Research Council, 1996).

- *Co-benefits*. An issue in both climate and development policy, related in some cases to access to financial support (e.g., Miller, 2008), is the fact that a specific resilience-enhancing action may have benefits for both development and for addressing concerns about climate change. International funding for mitigation projects has often adopted the concept of "additionality," which takes the position that financial support should be limited to those climate change response benefits that are *in addition to* what would be happening in development processes otherwise (e.g., Muller, 2009). This general concept (e.g., "incremental" costs and benefits) has been applied in financial support for adaptation as well. A co-benefits approach, on the other hand, takes the position that actions that benefit *both* development and climate change responses simultaneously should be encouraged and that a combination of both kinds of benefits should increase the attractiveness of a proposed action (Section 20.3.3). Co-benefits of mitigation actions, such as health benefits, have been extensively analyzed (e.g., Younger et al., 2008; Netherlands Environmental Assessment Agency, 2009; WHO, 2011; EPA, 2012), and they are being actively explored for adaptation as well (e.g., National Research Council, 2010a; UNFCCC, 2011).

As an example of co-benefits, mechanisms such as REDD+ have the potential to achieve both carbon emissions reduction and to benefit livelihoods of those living in forested areas, as well as supporting benefits to social equity (Anglesen et al., 2009; UNEP, 2013). As one instance, the government of Ethiopia has recognized the multiple benefits that can be derived and has incorporated a REDD+ initiative in critical sectors of the economy to develop an environmentally sustainable growth path in Ethiopia (FDRE, 2011). Tools for analyzing such issues are associated with research on "externalities" (e.g., Baumol and Oates, 1988; Klenow and Rodriguez-Clare, 2005; also see Chapter 17 and multi-metric valuations above), but participative planning and decision making usually incorporate a co-benefits perspective as a matter of course.

In practice, trade-offs between different development goals (Stoorvogel et al., 2004) may or not be resolved in coherent ways (Metz et al., 2002). In many cases, resolutions emerge through untidy social processes of evolution and attrition, reflecting dynamics of values, power, control, and surprises, rather than through formal analysis (Bizikova et al., 2008). In some cases, trade-offs are addressed with the assistance of scenario development, the creation of descriptive narratives, and other projections of future contingencies (IPCC, 2012, Chapter 8), along with participative vulnerability assessments (National Research Council, 2010a).

20.4.2. Ensuring Effective Institutions in Developing, Implementing, and Sustaining Resilient Strategies

Climate-resilient pathways will benefit from institutions that are effective and flexible in the face of a wider range of challenges, of which climate change is only one (Gupta et al., 2010). Governance systems, including public and private organizations, will need resources (e.g., human, financial, political, technological) to enable vulnerable societies that are sensitive to the impacts of climate change to transform their lives. Effective management of natural capital and ecosystem goods and services can be accomplished only where there are strong institutions as stewards and a regulatory force to ensure that vulnerable communities are protected from climate shocks and stresses and that growth from climate change is inclusive (Mitchell and Tanner, 2006). Moderating the impacts of climate change will also require strong a foundation in science and technology; but the deployment of science and relevant technologies cannot take place in a vacuum. It will need effective institutional arrangements to bolster both adaptation and mitigation demands and to combine technology options with local knowledge (Section 20.4.3).

"Institutions" refer not only to formal structures and processes but also to the rules of the game and the norms and cultures that underpin environmental values and belief systems (see Glossary). Ostrom (1986) defines institutions as the rules, norms, and practices defining social behavior in a particular context—the action arena. Institutions define roles and provide social context for action and structure social interactions (Hodgson, 2003). Definitions of sustainability are shaped largely by institutional values, cultures, and norms. Institutions also critically influence our ability to govern and manage the resources and systems that shape adaptation, mitigation, and sustainable development. Fostering climate-resilient pathways requires strong institutions that are able to create an enabling environment through which adaptive and mitigative capacities can be built (IPCC, 2007a, Chapter 20; Gupta et al., 2010). Implicit in institutional resilience is the capacity of the exposed unit and the players within an action arena to devise rules that allows them to recover from environmental shocks, and equally ones that provide incentives and benefits that equitably distribute resources across social groups (Handmer and Dovers, 1996; McSweeny and Coomes, 2011). Hence, the trajectory to a climate-resilient pathway requires institutional arrangements that foster innovation, monitoring, and evaluation of strategies for managing climate impacts and reducing risks.

Transformative action within a framework of climate-resilient pathways is rooted in strong and viable institutions and in an institutional context that adaptively manages the allocation of resources and processes of change. Institutions at different levels are the object of societal pressures and challenges relating to environmental change. Local institutions are particularly adroit in coping with multiple changes. These changes often force local actors and organizations to rethink their institutional arrangements and make adjustments that will allow them to cope with multiple vulnerabilities (McSweeny and Coomes, 2011), and their bottom-up initiatives are critically important to climate-resilient pathways. Organizational mechanisms are central to building linkages between local level adaptation action and national level planning. In six case studies in West Africa and Latin America, Agrawal et al. (2011) found that these connections are missing in all the countries studied. However, in these countries external policy support catalyzed adaptation actions

through three types of intervention mechanisms: information, incentives, and institutions.

Local institutions crucially influence the ability of communities to adapt and benefit from adaptation and mitigation programs in rural and urban settings (Corbera and Brown, 2008; Chhartre and Agrawal, 2009; Agrawal, 2010). For instance, institutions tend to play an influential role in shaping farmers' decisions and helping them make strategic choices with several implications for livelihoods and sustainable development (Agrawal, 2010). In rural areas, current socioeconomic dynamics, rapid population growth, commercialized agriculture, new agricultural trends, and technological advancements in agriculture have meant that local organizations and actors have seen a change in their role managing environmental resources; local institutions are themselves in a state of flux as they are subjected to uncertainties in climatic condition (Senaratne and Wickramasinghe, 2010). However, in developing countries, particularly in Africa, where traditional knowledge could potentially moderate this uncertainty, it is often not recognized as a reference point for managing climate risks and emerging threats. In Kenya, the importance of indigenous knowledge, given increased uncertainty and climate-related risks, has compelled national agencies such as the Kenyan Meteorological Agencies and vulnerable groups such as the indigenous communities commonly known as rainmakers to form strategic reciprocal links. By working closely together to calibrate their forecasts and test the efficacy of the results against climate change impacts on agricultural productivity, the two groups have been able to demonstrate the benefits of Western science and traditional knowledge systems to increase effectiveness (Ziervogel and Opere, 2010). In integrating different kinds of knowledge, participatory processes, which call for a deliberative form of decision making among stakeholders, are well suited to the governance culture necessary for effective adaptation and mitigation. However, findings in the literature regarding the effectiveness of participatory processes are mixed. For example, though some scholars have argued that deliberative democracy methods can bring diverse stakeholders and kinds of knowledge (e.g., lay, expert, and indigenous) together thus putting in place a more communicative model of science delivery (Benn et al., 2009), empirical research shows that stakeholder participation does not always lead to consensus (Rowe and Frewer, 2004; Bell et al., 2011; also see Salter et al., 2010).

In addition, better institutions are needed to handle the large flows of funds and other resources that are associated with managing and improving the delivery systems that will allow people and organizations to take advantage of opportunities that will trigger a set of actions to combat the negative impacts of climate change. The complexity of different resource flows and distributional effects related to adaptation and mitigation is at the heart of the sustainable development debate, with numerous implications for equity and justice (O'Brien and Leichenko, 2003; Roberts and Parks, 2006). The nature and dynamics of climate change call for flexibility to "allow society to modify its institutions at a rate commensurate with the rapid rate of environmental change" (Gupta et al., 2008). Here, institutional "renewal" is essential to achieve a degree of social cohesion and transformation.

An institutional response to climate change is even more fundamental in common pool property resources such as freshwater, especially because in a changing climate, many river basins are subjected to increased precipitation or water scarcity that affects both their ecosystems and the resources that support the livelihoods of those communities dependent on them. The quality and performance of the organizations and mechanisms created to manage these resources are largely shaped by the rules they follow and the suitability of these rules to the social ecological system in which they are embedded (Bisaro et al., 2010). Indeed, a climate-resilient pathway is one that will not only manage biophysical changes, but also address inherent institutional asymmetries that can further reinforce current inequalities in the way common pool resources are managed. In this context, the monitoring and mediation capacities and the degree to which resource management organizations are embedded at different scales across the governance regime will largely shape its adaptive capacity and sustainability. Thus, the vulnerability of large river basins will largely depend not only on the changing biophysical conditions, but also on institutional architecture that is put in place to manage risks and build resilience. For example, Schlager and Heikkila (2011) argue that compacts that have fixed allocation rules tend to exhibit greater vulnerability to climate change mainly because the system is far too rigid and does not allow for much flexibility in dealing with the changing hydrologic regime. States such as Colorado in the USA have dealt with water scarcity more efficiently mainly because users of the basin have access to venues that allow them to design and review current rules (Schlager and Heikkila, 2011).

Common problems with institutional arrangements for adaptively managing natural resources include a frequent incompatibility of current governance structures with many of those that may be necessary for promoting social and ecological resilience. For example, some major tenets of traditional management styles have "in many cases operated through exclusion of users and the top-down application of scientific knowledge in rigid programmes" (Tompkins and Adger, 2004, p. 10).

20.4.3. Enhancing the Range of Choices through Innovation

Finally, climate resilience will in most cases depend on innovation, developing new ideas and options or adapting robust familiar ideas and options to meet emerging new needs and to respond to surprises (see also WGIII AR5 Chapter 6). As indicated in the previous section, integrated strategies for climate resilience can benefit from considering possibilities to develop new options through social, institutional, and technological innovation. For example, if a climate-resilient pathway for a particular region calls for coping with greater water scarcity, innovations might consider changes in water rights practices, improving the understanding of groundwater dynamics and recharge, improving technologies and policies for water use efficiency improvements, and in coastal areas the development of more affordable technologies for desalination (Lebel, 2005; National Research Council, 2010a). One key issue for risk management, therefore, is assessing needs for and possible benefits from targeting innovation efforts on critical vulnerabilities.

Innovations can include both technological and social changes, which in many cases are closely related (Rohracher, 2008; Raven et al., 2010), as technology and society evolve together (Kemp, 1994). An important characteristic of such socio-technical transitions are the interactions and conflicts between new, emerging systems and established regimes,

with strong actors defending business-as-usual (Kemp, 1994; Perez, 2002; IPCC, 2012).

Effective use of innovations depends on more than idea and/or technology development alone. Unless the innovations, the skills required to use them, and the institutional approaches appropriate to deploy them are effectively transferred from providers to users, effects of innovations—however promising—are minimized (IPCC, 2012). Challenges in putting science and technology to use for sustainable development have received considerable attention (e.g., Nelson and Winter, 1982; Patel and Pavit, 1995; National Research Council, 1999; International Council for Science, 2002; Kristjanson et al., 2009). These studies emphasize the wide range of contexts that shape both barriers and potentials and the importance of "co-production" of knowledge, integrating general scientific knowledge with other forms of knowledge (e.g., local, indigenous, practical knowledge, experience, and expertise). If obstacles related to intellectual property rights can be overcome, however, the growing power of the information technology revolution could accelerate the transfer of technologies and other innovations (linked with local knowledge) in ways that would be very promising for strengthening local resilience (Wilbanks and Wilbanks, 2010).

New technologies have the potential to allow a number of developing countries to benefit from knowledge in ways that will give them considerable advantage in building the relevant social and institutional infrastructure to sustain a climate-resilient pathway. Advances in mobile technologies in developing countries, for example, have increased the accessibility of farmers to critical information such as disease surveillance, information related to agricultural inputs, and market prices for crops (Hazell et al., 2010; Juma, 2011). Biotechnology applications in biological systems have the potential to lead to increased food security and sustainable forestry practices, as well as improving health in developing countries by enhancing food nutrition.

20.5. Determinants of Resilience in the Face of Serious Threats

Climate change is not the only type of change occurring in the 21st century. Many households, communities, organizations, countries, and regions are confronting a confluence of economic, political, demographic, social, cultural, and environmental changes. Issues such as poverty, economic crisis, increasing inequality, and violent conflict often draw attention away from concerns about climate change, the loss of biodiversity and ecosystem services, and other global environmental issues. However, the impacts of climate change and extreme events can exacerbate food insecurity, slow down the pace of poverty reduction in urban areas, influence human health, and jeopardize sustainable development (Chapters 11, 12, 13). Resilience is a concept that takes into account how systems, communities, sectors, or households deal with disturbance, uncertainty, and surprise over time, and it is characterized by both adaptability and transformability (Walker and Salt, 2006; Folke et al., 2010; Westley et al., 2011). The sections below consider two important components of climate-resilient pathways: transformational adaptation in response to the impacts of climate change, and transformational change to reduce vulnerability and the risk of high-magnitude climate change.

20.5.1. Relationships between the Magnitude and Rate of Climate Change and Requirements for Transformational Adaptation

The timing and ambition levels of global GHG mitigation efforts will influence the magnitude and rate of climate change and its impacts, particularly in the second half of the 21st century and beyond (Kriegler et al., 2012; Peters et al., 2013; Rogelj et al., 2013; see also Box 20-3). Model results based on integrated scenarios that take into account geophysical, technological, social, and political uncertainties indicate that reaching the often-discussed limit of a 2°C average global temperature increase calls for mitigation of emissions through increased energy efficiency and lower energy demand well before 2020 (Peters et al., 2013; Rogelj et al., 2013; see also Section 20.6.1). If the magnitude and rate of climate change is kept minimal or moderate, incremental adaptation may be a sufficient response to consequences in many locations and contexts. However, in cases where vulnerability is currently high, transformational adaptation may be needed to respond to changes in climate and climate variability. In the absence of ambitious mitigation efforts, the impacts of climate change can be expected to increase dramatically from the second half of the 21st century onward (see Chapter 19). In this case, transformational adaptation may be required in advance of disruptive impacts to reduce risks and vulnerabilities (Kates et al., 2012).

This distinction between incremental and transformational adaptation is important: incremental adaptation can be considered extensions of actions and behaviors that already are in place to reduce losses or enhance benefits associated with climate change, often where the goal is to maintain the essence and integrity of an existing system or process at a given scale (Kates et al., 2012; Park et al., 2012). Transformational adaptation, in contrast, includes actions that change the fundamental attributes of a system in response to actual or expected impacts of climate change. These may involve adaptations at a larger scale or greater intensity than previously experienced; adaptations that are new to a region or system; or adaptations that transform places or lead to a shift in the location of activities (Kates et al., 2012). Such transformations are expected to occur when the rate and magnitude of climate change threatens to overwhelm the resilience of existing systems, or when vulnerability is high (Kates et al., 2012). Transformational adaptation often occurs in continuous interaction with incremental adaptations (see IPCC, 2012, Figure 8-1; Park et al., 2012). Although thresholds or tipping points in complex systems are difficult to predict, studies from a variety of disciplines indicate some generic properties associated with transitions between different states, including an increase in recovery times from disturbances such as extreme weather events (Scheffer et al., 2009; Lenton, 2011a). The risks associated with a high magnitude and rate of climate change and its impacts on natural and managed resources and systems are considerable. The limits to adaptation (Chapter 16) suggest that transformational change may be a requirement for sustainable development in a changing climate (Westley et al., 2011; O'Brien, 2012).

20.5.2. Elements of and Potentials for Transformational Change

Transformational change can be considered a means of reducing risk and vulnerability, not only by adapting to the impacts of climate change,

but also by challenging the systems and structures, economic and social relations, and beliefs and behaviors that contribute to climate change and social vulnerability. In cases where current development pathways are considered as the root causes of climate risk and vulnerability, transformation of wider political, economic, and social systems may be necessary (Pelling, 2010; IPCC, 2012; Lemos et al., 2013).

Transformation is defined as a change in the fundamental attributes of natural and human systems (see Glossary). Within the WGII AR5, transformation could reflect strengthened, altered, or aligned paradigms, goals, or values towards promoting adaptation for sustainable development, including poverty reduction. Transformations can occur quite suddenly, in response to a specific event or a momentous incident, or they may emerge gradually over time (Loorbach, 2007). Transformational change is often difficult to order or plan, and there are many social, political, and cultural barriers and resistances. Transformational change can threaten vested interests, or prioritize the interests of some over the well-being of others, and it is never a neutral process (Meadowcroft, 2009; Smith and Stirling, 2010). At the national level, transformation is considered most effective when it considers a country's own visions and approaches to achieve sustainable development in accordance with their national circumstances and priorities. While not every transformation is considered ethical, equitable, or sustainable, it is possible to promote deliberate transformations that reduce climate risk and vulnerability and contribute to global sustainability (Folke et al., 2010; Kates et al., 2012; O'Brien, 2012).

There is an extensive literature on transitions and transformations covering a variety of sectors and factors that influence changes in systems and behaviors (Geels, 2002; Calvin et al., 2009; Berkhout et al., 2010; Pelling 2010; Shove and Walker, 2010; WGIII AR5 Chapter 6). Transformations can be promoted by creating enabling conditions, which include a supportive social environment, information flows, and access to options, resources, and incentives for change (Kates et al., 2012). Transformations can also be stimulated through rules and regulations that necessitate innovations, alternative options, or new behaviors. Finally, transformations may result when alternative systems and structures eventually make old ones seem outdated. Often, dramatic focal events can draw attention to the need for change and mobilize groups or networks to advocate transformational change (Hernes, 2012).

Transformation processes are linked to learning, leadership, empowerment, and collaboration within and across institutions, organizations, and groups (Heifetz et al., 2009; IPCC, 2012, Chapter 8; Kates et al., 2012; O'Brien, 2012). Other key elements associated with transformations include adaptable institutions (cultural, economic, and governance), all types of capital, diversity in landscapes, seascapes and institutions, learning platforms, collective action and networks, as well as reflexivity and the capacity to take different perspectives (Loorbach 2007; Folke et al., 2010; Schlitz et al., 2010; Westley et al., 2011). Many of the elements of climate-resilient pathways discussed in Box 20-3 can, in fact, support transformation.

Transformations can take place within diverse realms or spheres (see Figure 20-2). Within each sphere, there exist both catalysts and constraints to transformation. The core of transformational change occurs in what is labeled in Figure 20-2 as the "practical sphere." Here,

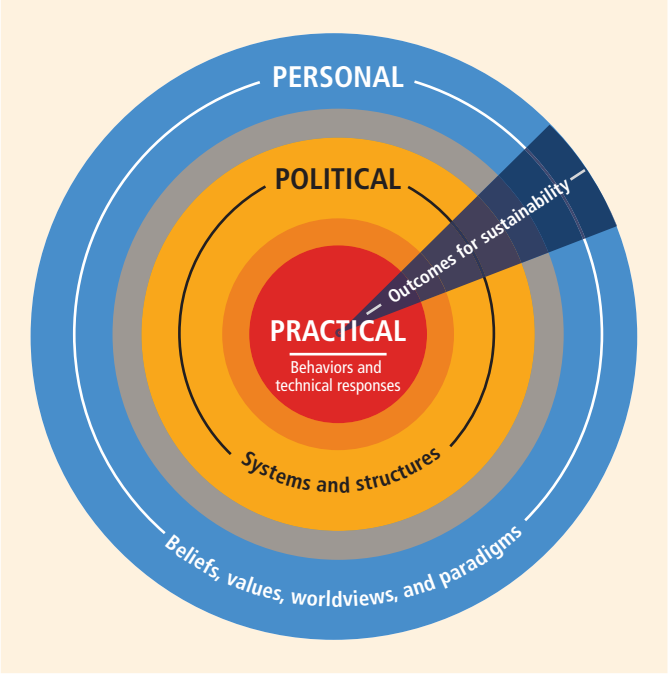

Figure 20-2 | The three spheres of transformation. Transformational change may be an effective leverage point for promoting climate-resilient pathways for sustainable development. This figure depicts three interacting spheres or realms where transformational changes toward sustainability may be initiated. Transformations in the outer two spheres can have a large influence on behaviors and technical responses, contributing to nonlinear transformations to sustainability (O'Brien and Sygna, 2013).

measures such as technological innovations and economic incentives are used to influence sustainable behaviors and responses. The outcomes of transformations in this sphere are observable and measurable; many sustainability policies and initiatives target transformations in this sphere. However, these transformations are often constrained by larger systems and structures, including financial, political, legal, social, economic, ecological, and cultural systems that define the boundaries for action. The "political sphere" is where systems and structures are transformed (intentionally or unintentionally) through politics and social movements, or through changes in social and cultural norms and power relations. Systems and structures often reflect dominant cultural beliefs and worldviews, and it is here where value conflicts may be experienced or resolved. A third sphere of transformation is the "personal sphere," which includes individual and collective beliefs, values, and worldviews, as well as the dominant paradigms. Transformations in this sphere can influence systems, structures, behaviors, and responses, and thus they represent important leverage points for sustainability. Attention to transformations in all three spheres is considered necessary in response to the observed and anticipated impacts of climate change (Beddoe et al., 2009; O'Brien and Sygna, 2013).

20.6. Toward Climate-Resilient Pathways

20.6.1. Alternative Climate-Resilient Pathways

Climate-resilient pathways consist of future trajectories of development that combine adaptation and mitigation in the context of sustainable

development implementation. At any scale (local or regional) there are alternative paths leading to similar levels of climate resilience (Holling, 1973). At any time along a pathway, more or less resilience may be observed at specified points within the system (or locality), while the total amount of resilience within the entire system remains unchanged (Folke, 2006). Each potential alternative pathway can be strengthened and evaluated based on certain risk management characteristics/elements: the capacity to (1) foresee risk/vulnerability; (2) decrease climate change impacts; (3) respond rapidly to unpredictable, uneven, and extreme events; (4) include considerable amounts of proactive adaptation; and (5) evolve in support of societal advancement and balanced environmental management.

Examples in this chapter demonstrate that many of the choices involved in framing and supporting attempts to increase and sustain climate resilience are made largely at global and national levels, but many of the actions to sustain resilience are made at local levels. The global pathways that emerge are accumulations of these local and national choices. In these processes, path dependence is strong enough such that risk management decisions in the near term are more likely to lead to resilience if long-term objectives are included as well as a wider spatial scale up to and including the global level.

A central issue in considering alternative pathways is the extent to which they may fail to meet a criterion of climate resilience. Or to put the question more simply, "are there any boundaries on the envelope of climate resilience?" The answer is highly scale dependent. We have a carbon legacy in the atmosphere, and total prevention/avoidance of impacts is now unachievable (Dickinson, 2007). At any level of stabilization of GHG concentrations, with even the strongest emissions reduction targets, some localities or systems or populations will be vulnerable to disruptions because there is in effect no limit below which universal prevention of residual loss and damages can be assured. Transformational change will therefore need to be a key component in nearly all alternative climate-resilient pathways.

In the event that global surface mean temperatures rise through +2°C to +4°C and higher (Anderson and Bows, 2008; Schneider, 2008; New et al., 2012), sustainability will become significantly more difficult to achieve (food security is a notable example; see Chapter 7). For example, a business-as-usual future society where unsustainable development paths are the norm, where technology transfer between countries is lacking, population growth increases rapidly, GHG emission go unabated, and institutions and governance structures are ineffective at creating effective climate change policies, would almost certainly result in losses so widespread that a development pathway would not be resilient (Riahi et al., 2011; Arnell et al., 2013). A pathway that included these elements would fall outside the "boundaries of the envelope of climate resilience."

Within these boundaries, climate-resilient pathways can be made up of a collective of alternative choices at the regional level, where they are dependent upon specific demographics, potentials for economic development and growth, ecological and ecosystem services, access to natural resources, institutional and governance structures, and technological development and transfer. This concept at the global level offers a conceptual framework for considering alternative mixes of actions in support of climate resilience. Pathways can be developed to illustrate a range of possible futures, as a basis for discussion, following different yet distinct storylines. These dimensions can then be related to socioeconomic challenges confronting climate change mitigation and adaptation (as one aspect of sustainable development). One such pathway could have relatively limited challenges to both adaptation and mitigation, while another has substantial challenges to both adaptation and mitigation. Any pathway characterized by low challenges to both has a high potential to be more climate resilient at the global scale and in many local or national situations. A pathway characterized by high challenges to both adaptation and mitigation has a high potential to be less climate resilient at the global scale and in many localities and countries.

20.6.2. Implications for Current Sustainable Development Strategies and Choices

Decision makers face an array of choices in their efforts to define and implement pathways that will help to improve human well-being now and in the future in the face of climate change and other stressors.

Although payoffs from specific long-term pathways may be uncertain at this time, growing evidence (IPCC, 2007; see also Chapters 8 to 13, 16 to 19) suggests that decision points and actions are at hand now. Climate-resilient development pathways are not only about actions taken in the future, but they are also about strategies and choices that are taken today. In fact, damage and loss patterns are not limited to future vulnerabilities; in many areas they are impeding food production and other essential development services in ways that deepen and widen poverty (Chapter 13), contribute to involuntary migration (Chapter 12; Warner and Afifi, 2013), and pressure food production and food prices (Chapters 7, 17; Warner and van der Geest, 2013).

In this sense, delaying action in the present may reduce options for climate-resilient pathways in the future. In some parts of the world,

Frequently Asked Questions

FAQ 20.4 | Are there things that we can be doing now that will put us on the right track toward climate-resilient pathways?

Yes. Climate-resilient pathways begin now, because it is time to consider possible strategies that would increase climate resilience while at the same time helping to improve human livelihoods and social and economic well-being. Combining these strategies with a process of iterative monitoring, evaluation, learning, innovation, and contingency planning will reduce climate change disaster risks, promote adaptive management, and contribute significantly to prospects for climate-resilient pathways.

inadequate efforts to address effects of emerging climate stressors are already eroding the basis for sustainable development. New studies find that among people who attempt to cope with current stresses, most experienced negative residual impacts and as a consequence faced eroding household income and food security, health, and education opportunities and were more likely to migrate and lose housing and livelihood assets (Monnereau and Abraham, 2013; Rabbani et al., 2013; Traore et al., 2013; Warner and van der Geest, 2013; Yaffa, 2013). For example, in the Punakha district in Bhutan, 87% of households that adopted coping measures reported that they were still experiencing adverse effects of changing monsoon patterns despite the adaptation measures (Kusters and Wangdi, 2013). Evidence (Chapters 7, 8, 12, 13, 16, 19) suggests that waiting to take more effective action may reduce the range of choices for climate-resilient pathways in the future (National Research Council, 2011).

More generally, IPCC (2012) makes the case that a window of opportunity exists now for considering possible strategies that would increase climate resilience while at the same time helping to improve human livelihoods and social and economic well-being. It suggests that a process of iterative monitoring, evaluation, learning, innovation, and contingency planning will reduce climate change disaster risks, promote adaptive management, and contribute significantly to prospects for climate-resilient pathways. In this sense, strategies and actions can be pursued now that will move toward climate-resilient pathways while at the same time helping to improve human livelihoods, social and economic well-being, and responsible environmental management.

As policy makers explore what pathways to pursue, they will increasingly face questions about managing discourses about what societal objectives to pursue unchanged, where compromises in objectives are tolerable, and what consequences including loss and damage may be associated with different pathways. In considering possible needs for transformational pathways (Section 20.5), extreme weather occurrences such as major floods, wildfires, cyclones, and heat waves may focus societal attention on vulnerabilities and stressors and provide a "policy window" for major changes (Kingdon, 1995; Birkland, 2006; Kates et al., 2012). Discussions of transformation may require broader-based social discourse (Pelling et al., 2007) and iterative institutional learning (Berkhout et al., 2006), on the basis of growing evidence, knowledge, and experience. Systems to monitor emerging stresses and threats will aid decision makers at different scales to evaluate alternative pathways (Kates et al., 2012).

20.7. Priority Research/Knowledge Gaps

Because integrating climate change mitigation, climate change adaptation, and sustainable development is a relatively new challenge, research should be a very high priority indeed to inform strategies and actions. The most salient research need is to improve the understanding of how climate change mitigation and adaptation can be combined with resilient sustainable development pathways in a wide variety of regional and sectoral contexts (Wilbanks, 2010). One starting point is simply improving the capacity to characterize benefits, costs, potentials, and limitations of major mitigation and adaptation options, along with their external implications for equitable development, so that integrated climate change response strategies can be evaluated more carefully (Wilbanks et al., 2007; National Research Council, 2011). What are the major trade-offs? What are the potential synergies? How do implications of integrated mitigation/adaptation strategies vary with location, climate change risks and vulnerabilities, scale, and development objectives and capacities (e.g., Hugé et al., 2011)? In these regards, the best of global science needs to be combined with national and local expertise to advance knowledge related to climate-resilient pathways.

Related to this general priority are at least three specific research needs:

- Advances in conceptual and methodological understandings of, and tools to support research on, multiple drivers of development pathways and climate change impacts; possible feedback effects among mitigation, adaptation, and development; possible thresholds/tipping points that could cause particular challenges for development; and possible transformations to reduce losses and damages and support sustainable development (Stern and Wilbanks, 1999; National Research Council, 2010a; see also Section 20.5).
- Advances in knowledge about how to respond sustainably to climate change extremes and extreme events, when and where they pose development challenges that would appear to require transformative changes in affected human and/or environmental systems. What might the response options be, and how can they be facilitated where they merit consideration (e.g., Pelling, 2010; Lemos et al., 2013)?
- Research on how to reconcile the importance of synergies between climate change adaptation and mitigation actions with widespread use of the concept of "additionality." For example, how might criteria be established for access to financial support for adaptation that incorporates the development importance of co-benefits? Such research could inform discourses about differences between adaptation and development in ways that enable the flow of financial resources to support adaptations (National Research Council, 2010a).

Further research needs include:

- Research attention to potentials for technological and institutional innovations to ease threats to sustainable development from climate change impacts and responses. In other words, how might climate change responses represent opportunities for innovative development paths? How might technological development be part of a strategy for development/climate change response integration (Wilbanks, 2010)?
- Research on strategies for institutional development, including improving understanding of how social institutions affect resource use (Stern and Wilbanks, 1999), improving understanding of risk-related judgment and decision-making under uncertainty (Stern and Wilbanks, 1999), and best practices in creating institutions that will effectively integrate climate change responses with sustainable development characteristics such as participation, equity, and accountability.
- Research on strategies for the implementation of adaptive management and risk reduction for development. Examples of important research needs include improving the understanding of respective roles and interactions between autonomous response behavior and policy initiatives; improving the body of empirical evidence about how to implement changes that are judged to be desirable, for example, adaptive management and governance capacity; and improving the understanding of differences between

retrofitting older infrastructures (challenge in many industrialized countries) and designing new infrastructures (challenge in many rapidly developing countries) (IPCC, 2012, Chapter 8).

- Research to improve the understanding of how to build social inclusiveness into development/climate change response integration. As suggested above, research is needed on issues of social values/climate justice/equity/participation and how they intersect with the deployment of mitigation, adaptation interventions, and sustainable development policy in different regional/sociopolitical contexts (IPCC, 2012, Chapter 8).
- Research on factors that influence deliberate transformations that are ethical, equitable, and sustainable (Kates et al., 2012; O'Brien, 2012).
- The development of structures for learning from emerging integrated climate change response/development experience, for example, approaches and structures for monitoring, recording, evaluating, and learning from experience and identifying "best practices" and their characteristics (National Research Council, 2010a; Hilden, 2011; IPCC, 2012, Chapter 8).

Finally, it is very possible that progress with global climate change mitigation will not be sufficient to avoid relatively high levels of regional and sectoral impacts, and that such conditions would pose growing challenges to the capacity of adaptation to avoid serious disruptions to development processes. If this were to become a reality later in this century, one response could be a rush toward geoengineering approaches. In preparation for such a contingency, and perhaps as an additional way to show how important progress with mitigation will be in framing prospects for sustainable development in many contexts, there is a very serious need for research on geoengineering costs, benefits, risks, a wide range of possible impacts, and fair and equitable structures for global policy and decision making (UK Royal Society, 2009; Kates et al., 2012).

But a fundamental aim of research to improve capacities for climate-resilient pathways for sustainable development is to avoid such an unfortunate outcome. It seeks to do so by strengthening the base of knowledge that underlies and supports effective actions by viewing climate change mitigation, climate change adaptation, and sustainable development in an integrative and mutually supportive way.

References

ADB and ADBI, 2012: *Low-Carbon Green Growth in Asia: Policies and Practices.* Joint study of the Asian Development Bank (ADB) and the Asian Development Bank Institute (ADBI), ADB, Manila, Philippines, 246 pp.

Adger, W.N., 2010: Climate change, human well-being, and insecurity. *New Political Economy*, **15(2)**, 275-292.

Adger, W.N., S. Huq, K. Brown, D. Conway, and M. Hulme, 2003: Adaptation to climate change in the developing world. *Progress in Development Studies*, **3**, 179-195.

Adger, W.N., K. Brown, D.R. Nelson, F. Berkes, H. Eakin, C. Folke, K. Galvin, L. Gunderson, M. Goulden, and K. O'Brien, 2011: Resilience implications of policy responses to climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **2(5)**, 757-766.

Agrawal, A., 2010: Local institutions and adaptation to climate change. In: *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World* [Mearns, R. and A. Norton (eds.)]. The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, pp. 173-198.

Agrawal, A., R. Mearns, N. Perrin, and M. Kononen, 2011: *Area-Based Development, Local Institutions & Climate Adaptation: A Comparative Analysis from West Africa and Latin America.* The World Bank Group, Washington, DC, USA, 56 pp.

Agrawala, S. and M. van Aalst, 2008: Adapting development cooperation to adapt to climate change. *Climate Policy*, **8(2)**, 183-193.

Anderson, K. and A. Bows, 2008: Reframing the climate change challenge in light of post-2000 emission trends. *Philosophical Transactions of the Royal Society A*, **366(1882)**, 3863-3882.

Angelson, A., 2009: *Realizing REDD+: National Strategy and Policy Options.* Center for International Forestry Research (CIFOR), Bogor, Indonesia, 362 pp.

Arndt, C., P. Chinowsky, S. Robinson, K. Strzepek, R. Tarp, and R. Thurlow, 2012: Economic development under climate change. *Review of Development Economics*, **16(3)**, 369-377, doi: 10.1111/j.1467-9361.2012.00668.x.

Arnell, N.W., J.A. Lowe, S. Brown, S.N. Gosling, P. Gottschaalk, J. Hinkel, B. Lloyd-Hughes, R.J. Nicholls, T.J. Osborn, T.M. Osborne, G.A. Rose, P. Smith, and R.F. Warren, 2013: A global assessment of the effects of climate policy on the impacts of climate change. *Nature Climate Change*, **3**, 512-519.

Auerswald, H., K. Konrad, and M.P. Thum, 2011: *Adaptation, Mitigation and Risk-Taking in Climate Policy.* CESifo Working Paper No. 3320, Category 10: Energy and Climate Economics, The CESifo Group: the Center for Economic Studies (CES), the Ifo Institute and the Munich Society for the Promotion of Economic Research (CESifo GmbH), The CESifo Group, Munich, Germany, 22 pp.

Ayers, J.M. and S. Huq, 2009: The value of linking mitigation and adaptation: a case study of Bangladesh. *Environmental Management*, **43(5)**, 753-764.

Bäckstrand, K., 2003: Civic science for sustainability: reframing the role of experts, policy-makers and citizens in environmental governance. *Global Environmental Politics*, **3(4)**, 24-41.

Bamuri, T. and M.H. Opeschoor, 2007: Climate change and sustainable development: realizing the opportunity. *Ambio*, **35(1)**, 2-8.

Banerjee, S.B., 2012: A climate for change? Critical reflections on the Durban United Nations Climate Change Conference. *Organization Studies*, **33(12)**, 1761-1786, doi:10.1177/0170840612464609.

Barker, T., 2008: The economics of avoiding dangerous climate change. An editorial essay on The Stern Review. *Climatic Change*, **89(3-4)**, 173-194.

Baumol, W. and W. Oates, 1989: *The Theory of Environmental Policy.* Cambridge University Press, Cambridge, UK, 299 pp.

Beckman, M., 2011: Converging and conflicting interests in adaptation to environmental change in central Vietnam. *Climate and Development*, **3**, 32-41.

Beddoe, R., R. Costanza, J. Farley, E. Garza, J. Kent, I. Kubiszewski, L. Martinez, T. McCowen, K. Murphy, N. Myers, Z. Ogden, K. Stapleton, and J. Woodward, 2009: Overcoming systemic roadblocks to sustainability: the evolutionary redesign of worldviews, institutions, and technologies. *Proceedings of the National Academy of Sciences of the United States of America*, **106(8)**, 2483-2489.

Beg, N., J.C. Morlot, O. Davidson, Y. Afrane-Okesse, L. Tyani, F. Denton, Y. Sokona, J.P. Thomas, E.L. La Rovere, J.K. Parikh, K. Parikh, and A.A. Rahman, 2002: Linkages between climate change and sustainable development. *Climate Policy*, **2(2-3)**, 129-144.

Bell, A., N. Engle, and M. Lemos, 2011: How does diversity matter? The case of Brazilian river basin councils. *Ecology and Society*, **16(1)**, 42, www.ecologyandsociety.org/vol16/iss1/art42/.

Benn, S., D. Dunphy, and A. Martin, 2009: Governance of environmental risk: new approaches to managing stakeholder involvement, *Journal of Environmental Management*, **90**, 1567-1575.

Berkes, F., 2007: Understanding uncertainty and reducing vulnerability: lessons from resilience thinking. *Natural Hazards*, **41**, 283-295.

Berkhout, F., J. Hertin, and D.M. Gann, 2006: Learning to adapt: organizational adaptation to climate change impacts. *Climatic Change*, **78**, 135-156.

Berkhout, F., G. Verbong, A.J. Wieczorek, R. Raven, L. Lebel, and X. Bai, 2010: Sustainability experiments in Asia: innovations shaping alternative development pathways? *Environmental Science and Policy*, **13**, 261-271.

Bierbaum, R., J.B. Smith, A. Lee, M. Blair, L. Carter, F.S. Chapin, P. Fleming, S. Ruffo, M. Stultz, S. McNeeley, E. Wasley, and L. Verduzzo, 2013: A comprehensive review of climate adaptation in the United States: more than before, but less than needed. *Mitigation and Adaptation Strategies for Global Change*, **18(3)**, 361-406.

Biesbroek, G.R., J. Swart, and W.G.M. van der Knaap, 2009: The mitigation-adaptation dichotomy and the role of spatial planning. *Habitat International*, **33(3)**, 230-237.

Birkland, T.A., 2006: *Lessons of Disaster: Policy Change After Catastrophic Events.* Georgetown University Press, Washington, DC, USA, 216 pp.

Bisaro, A., J. Hinkel, and N. Kranz, 2010: Multilevel water, biodiversity, and climate adaptation governance: evaluating adaptive management in Lesotho. *Environmental Science & Policy*, **13**, 637-647.

Bizikova, L., J. Robinson, and S. Cohen, 2007: Linking climate change and sustainable development at the local level. *Climate Policy*, **7**, 271-277.

Bizikova, L., T. Neale, and I. Burton, 2008: *Canadian Communities' Guidebook for Adaptation to Climate Change. Including an Approach to Generate Mitigation Co-Benefits in the Context of Sustainable Development.* 1st edn, Adaptation and Impacts Research Division (AIRD), Environment Canada and the University of British Columbia, Vancouver, Environment Canada, Toronto, ON, Canada, 100 pp.

Bizikova, L., S. Burch, S. Cohen, and J. Robinson, 2010: Linking sustainable development with climate change adaptation and mitigation. In: *Climate Change, Ethics and Human Security* [O'Brien, K., A. St. Clair, and B. Kristoffersen (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 157-179.

Blackstock, J.J. and J.C.S. Long, 2010: The politics of geoengineering. *Science*, **327(5965)**, 527, doi:10.1126/science.1183877.

Boyd, E., H. Osbahr, P.J. Ericksen, E.L. Tompkins, M.C. Lemos, and F. Miller, 2008: Resilience and climatizing development: examples and policy implications. *Development*, **51(3)**, 390-396.

Brooks, N., W.N. Adger, and P.M. Kelley, 2005: The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Global Environmental Change: Human and Policy Dimensions*, **15(2)**, 151-163.

Brovkin, V., V. Petoukhov, M. Claussen, E. Bauer, A. Archer, and C. Jaeger, 2009: Geoengineering climate by stratospheric sulfur injections: Earth system vulnerability to technological failure. *Climatic Change*, **92**, 243-259.

Brown, K., 2011: Sustainable adaptation: an oxymoron? *Climate and Development*, **3**, 21-31.

Brown, L., 1981: *Building a Sustainable Society.* W.W. Norton & Co. Inc., New York, NY, USA, 433 pp.

Bryan, E., C. Ringler, B. Okoba, J. Koo, M. Herrero, and S. Silvestri, 2013: Can agriculture support climate change adaptation, greenhouse gas mitigation and rural livelihoods? Insights from Kenya. *Climatic Change*, **118(2)**, 151-165.

Bulkeley, H. and H. Schroeder, 2012: Beyond state/non-state divides: global cities and the governing of climate change. *European Journal of International Relations*, **18(4)**, 743-766.

Burch, S., 2010: Transforming barriers into enablers of action on climate change: insights from three municipal case studies in British Columbia, Canada. *Global Environmental Change: Human and Policy Dimensions*, **20**, 287-297.

Burton, I., S. Huq, B. Lim, O. Pilifosova, and E.L. Schipper, 2002: From impact assessment to adaptation priorities: the shaping of adaptation policy. *Climate Policy*, **2**, 145-159.

Cafaro, P., 2010: Getting to less. *Ethics, Place, and Environment*, **13(1)**, 11-14.

Calvin, K., J. Edmonds, B. Bond-Lamberty, L. Clarke, S.H. Kim, P. Kyle, S.J. Smith, A. Thomson, and M. Wise, 2009: 2.6: Limiting climate change to 450 ppm CO_2 equivalent in the 21st century. *Energy Economics,* **31(Suppl. 2)**, S107-S120.

Campbell-Lendrum, D. and R. Woodruff, 2006: Comparative risk assessment of the burden of disease from climate change. *Environmental Health Perspectives*, **114**, 1935-1941.

Chhatre, A. and A. Agrawal, 2009: Trade-offs and synergies between carbon storage and livelihood benefits from forest commons. *Proceedings of the National Academy of Sciences of the United States of America*, **108(42)**, 17667-17670.

Chuku, C.A., 2009: Pursuing an integrated development and climate policy framework in Africa: options for mainstreaming. *Mitigation and Adaptation Strategies for Global Change*, **15(1)**, 41-52.

Chukwumerije, O. and H. Schroeder, 2009: How can justice, development and climate mitigation be reconciled for developing countries in a post-Kyoto settlement? *Climate and Development*, **1**, 10-15.

Clark, A.E., P. Frijters, and M.A. Shields, 2008: Relative income, happiness, and utility: an explanation for the Easterlin Paradox and other puzzles. *Journal of Economic Literature*, **46(1)**, 95-144.

Corbera, E. and K. Brown, 2008: Building institutions to trade ecosystem services: marketing forest carbon in Mexico. *World Development*, **36**, 1956-1979.

Crutzen, P.J., 2006: Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma? *Climatic Change*, **77(3-4)**, 211-220.

Crutzen, P.J. and E.F. Stoermer, 2000: The "Anthropocene". *Global Change Newsletter*, **41**, 17-18.

Dang, H.H., A. Michaelowa, and D.D. Tuan, 2003: Synergy of adaptation and mitigation strategies in the context of sustainable development: the case of Vietnam. *Climate Policy*, **3(Suppl. 1)**, S81-S96.

De Boer, J., J.A. Wardekker, and J.P. van der Sluijs, 2010: Frame-based guide to situated decision-making on climate change. *Global Environmental Change: Human and Policy Dimensions*, **20(3)**, 502-510.

Deaton, A., 2008: Income, health and well-being around the world: evidence from the Gallup World Poll. *Journal of Economic Perspectives*, **22**, 53-72.

Deere-Birbeck, C., 2009: Global governance in the context of climate change: the challenges of increasingly complex risk parameters. *International Affairs*, **85(6)**, 1173-1194.

DeLeire, T. and A. Kalil, 2010: Does consumption buy happiness? Evidence from the United States. *International Review of Economics*, **57(2)**, 163-176.

Dickinson, T. (ed.), 2007: *Compendium of Adaptation Models for Climate Change.* 1st edn., Adaptation and Impacts Research Division (AIRD), Environment Canada, Toronto, ON, Canada, 41 pp.

Dolan, P. and M.P. White, 2007: How can measures of subjective well-being be used to inform public policy? *Perspectives in Psychological Science*, **2**, 71-85.

Dovers, S.R. and A.A. Hezri, 2010: Institutions and policy processes: the means to the ends of adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, **1(2)**, 212-231.

Drouineau, H., J. Lobry, C. Delpech, M. Bouchoucha, S. Mahevas, A. Courrat, S. Pasquaud, and M. Lepage, 2012: A Bayesian framework to objectively combine metrics when developing stressor specific multimetric indicators. *Ecological Indicators*, **13**, 314-321.

Eakin, H., 2005: Institutional change, climate risk, and rural vulnerability: cases from central Mexico. *World Development*, **33**, 1923-1938.

Eakin, H. and M.C. Lemos, 2006: Adaptation and the state: Latin America and the challenge of capacity-building under globalization. *Environmental Change-Human and Policy Dimensions*, **16**, 7-18.

Easterlin, R.A., 1974: Does economic growth improve the human lot? In: *Nations and Households in Economic Growth: Essays in Honor of Moses Abramovitz* [David, P.A. and M.W. Reder (eds.)]. Academic Press, Inc., New York, NY, USA, pp. 89-125.

Easterlin, R.A., 2001: Income and happiness: toward a unified theory. *Economic Journal*, **111**, 465-484.

Edenhofer, O., J. Wallacher, H. Lotze-Campen, M. Reder, B. Knopf, and J. Müller, 2012: *Climate Change, Justice and Sustainability: Linking Climate and Development Policy.* Springer, Dordrecht, Netherlands, 401 pp.

Editorial Board of National Climate Change Assessment, 2011: *Second National Climate Change Assessment Report.* Editorial Board of National Climate Change Assessment (EBNCCA), Science Press, Beijing, China, 710 pp.

Ehrenfeld, J., 2008: *Sustainability by Design: A Subversive Strategy for Transforming Our Consumer Culture.* Yale University Press, New Haven, CT, USA, 246 pp.

Engle, N.L., 2013: The role of drought preparedness in building and mobilizing adaptive capacity in states and their community water systems. *Climatic Change*, **118(2)**, 291-306.

EPA, 2012: *Co-Benefits Risk Assessment (COBRA) Screening Model: A Tool that Estimates the Health and Economic Benefits of Air Quality Policies.* U.S. Environmental Protection Agency (EPA), Washington, DC, USA, epa.gov/statelocalclimate/resources/cobra.html.

Eriksen, S. and K. Brown, 2011: Sustainable adaptation to climate change. *Climate and Development*, **3(1)**, 3-6.

Eriksen, S., P. Aldunce, C.S. Bahinipati, R.D. Martins, J.I. Molefe, C. Nhemachena, K. O'Brien, F. Olorunfemi, J. Park, L. Sygna, and K. Ulsrud, 2011: When not every response to climate change is a good one: identifying principles for sustainable adaptation. *Climate and Development*, **3(1)**, 7-20, doi:10.3763/cdev.2010.0060.

Falloon, P. and R. Betts, 2010: Climate impacts on European agriculture and water management in the context of adaptation and mitigation – the importance of an integrated approach. *Science of the Total Environment*, **408(23)**, 5667-5687.

FDRE, 2011: *Ethiopia's Climate-Resilient Green Economy: Green Economy Strategy.* Federal Democratic Republic of Ethiopia (FDRE), Addis Ababa, Ethiopia, 188 pp.

Fleurbaey, M., 2009: Beyond GDP: the quest for a measure of well-being and social welfare. *Journal of Economic Literature*, **47**, 1029-1075.

Folke, C., 2006: Resilience: the emergence of a perspective for social-ecological systems analyses. *Global Environmental Change*, **16(3)**, 253-267.

Folke, C., S.R. Carpenter, T. Elmqvist, L. Gunderson, C.S. Holling, and B. Walker, 2002: Resilience and sustainable development: building adaptive capacity in a world of transformations. *Ambio*, **31**, 437-440.

Folke, C., S.R. Carpenter, B. Walker, M. Scheffer, T. Chapin, and J. Rockström, 2010: Resilience thinking: integrating resilience, adaptability and transformability. *Ecology and Society*, **15(4)**, 20, www.ecologyandsociety.org/vol15/iss4/art20/.

Forsyth, T., 2007: Promoting the "development dividend" of climate technology transfer: can cross-sector partnerships help? *World Development*, **35**, 1684-1698.

Frey, G.W. and D.J. Linke, 2002: Hydropower as a renewable and sustainable energy resource meeting global energy challenges in a reasonable way. *Energy Policy*, **30**, 1261-1265.

Gao, Q.-z., Y.-f. Wan, H.-m. Xu, Y. Li, W.-z. Jiangcun, and A. Borjigidai, 2010: Alpine grassland degradation index and its response to recent climate variability in Northern Tibet, China. *Quaternary International*, **226(1-2)**, 143-150.

Gao, Q.-z., Y. Li, H.-m. Xu, Y.-f. Wan, and W.-z. Jiangcun, 2012: Adaptation strategies of climate variability impacts on alpine grassland ecosystems in Tibetan Plateau. *Mitigation and Adaptation Strategies for Global Change*, **19(2)**, 199-209.

Gardiner, S., 2010: Ethics and climate change: an introduction. *Wiley Interdisciplinary Reviews: Climate Change*, **1(1)**, 54-56.

Gardiner, S.M., S. Caney, D. Jamieson, and H. Shue, 2010: *Climate Ethics: Essential Readings.* Oxford University Press, New York, NY, USA, 351 pp.

Garg, A., P.R. Shukla, and M. Kapshe, 2007: From climate change impacts to adaptation: a development perspective for India. *Natural Resources Forum*, **31**, 132-141.

Garg, A., R. Dahiman, S. Bhattacharya, and P.R. Shukla, 2009: Development, malaria and adaptation to climate change: a case study from India. *Environmental Management*, **43**, 779-789.

Geels, F.W., 2002: Technological transitions as evolutionary reconfiguration processes: a multilevel perspective and case study. *Research Policy*, **31(8-9)**, 1257-1274.

Goes, M., N. Tuana, and K. Keller, 2011: The economics (or lack thereof) of aerosol geoengineering. *Climatic Change*, **109**, 719-744.

Grist, N., 2008: Positioning climate change in sustainable development discourse. *Journal of International Development*, **20**, 783-803.

Gulledge, J., L.J. Richardson, L. Adkins, and S. Seidel (eds.), 2010: *Assessing the Benefits of Avoided Climate Change: Cost-Benefit Analysis and Beyond*. Proceedings of Workshop on Assessing the Benefits of Avoided Climate Change, Washington, DC, March 16-17, 2009, Pew Center on Global Climate Change: Arlington, VA, USA, 231 pp.

Gupta, J., K. Termeer, J. Klostermann, S. Meirjerirnk, M. van den Brink, P. Jong, and S. Nooteboom, 2008: *Institutions for Climate Change: A Method to Assess the Inherent Characteristics of Institutions to Enable the Adaptive Capacity of Society.* Institute for Environmental Studies, Amsterdam, Netherlands, 19 pp.

Gupta, J., C. Termeer, K. Klostermann, S. Meijerink, M. van den Brink, P. Jong, S. Nooteboom, and E. Bergsma, 2010: The adaptive capacity wheel: a method to assess the inherent characteristics of institutions to enable the adaptive capacity of society. *Environmental Science & Policy*, **13**, 459-471.

Hallegatte, S., 2009: Strategies to adapt to an uncertain climate change. *Global Environmental Change*, **19(2)**, 240-247.

Halsnaes, K. and J. Verhagen, 2007: Development based climate change adaptation and mitigation. Conceptual issues and lessons learned in studies in developing countries. *Mitigation and Adaptation Strategies for Global Change*, **12(5)**, 665-684.

Halsnaes, K., P.R. Shukla, and A. Garg, 2008: Sustainability development and climate change: lessons from country studies. *Climate Policy*, **8(2)**, 202-219.

Hamin, E.M. and N. Gurran, 2009: Urban form and climate change: balancing adaptation and mitigation in the US and Australia. *Habitat International*, **33**, 238-245.

Handmer, J. and S. Dovers, 1996: A typology of resilience: rethinking institutions for sustainable development. *Industrial and Environmental Crisis Quarterly*, **9(4)**, 482-511, doi: 10.1177/108602669600900403.

Hanjra, M.A. and M.E. Qureshi, 2010: Global water crisis and future food security in an era of climate change. *Food Policy*, **35**, 365-377.

Hardee, K. and C. Mutunga, 2009: Strengthening the link between climate change adaptation and national development plans: lessons from the case of population in National Adaptation Programmes of Action (NAPAs). *Mitigation and Adaptation Strategies for Global Change*, **15(2)**, 113-126.

Hazell, P., J. Anderson, N. Balzer, A. Hastrup-Clemmensen, U. Hess, F. Rispoli, K. Hardee, and C. Mutunga, 2010: *The Potential for Scale and Sustainability in Weather Index Insurance for Agriculture and Rural Livelihoods*. International Fund for Agricultural Development (IFAD) and World Food Programme (WFP) working jointly through the IFAD-WFP Weather Risk Management Facility (WRMF), Rome, Italy, 153 pp.

Heifetz, R., A. Grashow, and M. Linsky, 2009: *The Practice of Adaptive Leadership: Tools and Tactics for Changing Your Organization and the World.* Harvard Business School, Cambridge, MA, USA, 326 pp.

Heltberg, R., P.B. Siegel, and S.L. Jorgensen, 2009: Addressing human vulnerability to climate change: toward a no-regrets approach. *Global Environmental Change*, **19(1)**, 89-99.

Hernes, G., 2012: *Hot Topic – Cold Comfort: Climate Change and Attitude Change.* Nordem Top Research Initiative, Oslo, Norway, 158 pp.

Hilden, M., 2011: The evolution of climate policies: the role of learning and evaluations. *Journal of Cleaner Production*, **19**, 1798-1811.

Hodgson, G.M., 2003: The hidden persuaders: institutions and individuals in economic theory. *Cambridge Journal of Economics*, **27(2)**, 159-175.

Hof, A.F., K.C. de Bruin, R.B. Dellink, M.G.J. den Elzen, and D.P. van Vuuren, 2009: The effect of different mitigation strategies on international financing of adaptation. *Environmental Science & Policy*, **12**, 832-843.

Holling, C.S., 1973: Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, **4**, 1-23.

Huesemann, M.H., 2006: Can advances in science and technology prevent global warming? A critical review of limitations and challenges. *Mitigation and Adaptation Strategies for Global Change*, **11(3)**, 539-577.

Hueting, R., 2010: Why environmental sustainability can most probably not be attained with growing production. *Journal of Cleaner Production*, **18(6)**, 525-530.

Hugé, J., T. Waas, G. Eggermont, and A. Verbruggen, 2011: Impact assessment for a sustainable energy future: reflections and practical experiences. *Energy Policy*, **39**, 6243-6253.

International Council for Science, 2002: *Science and Technology for Sustainable Development: Consensus Report and Background Document, Mexico City Synthesis Conference, 20-23 May 2002*. ICSU Series on Science for Sustainable Development No. 9, International Council for Science (ICSU), Paris, France, 30 pp.

IPCC, 2007a: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 976 pp.

IPCC, 2007b: Summary for policymakers. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, (eds.)]. Cambridge University Press, UK and New York, NY, USA, pp. 7-22.

IPCC, 2011: *Special Report on Renewable Energy Sources and Climate Change Mitigation.* Prepared by Working Group III of the Intergovernmental Panel on Climate Change [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1075 pp.

IPCC, 2012: *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp.

Jerneck, A. and L. Olsson, 2008: Adaptation and the poor: development, resilience and transition. *Climate Policy*, **8**, 170-182.

Johnston, R., K. Segerson, E.T. Schultz, E.Y. Besedin, and M. Ramachandran, 2011: Indices of biotic integrity in stated preference valuation of ecosystem services. *Ecological Economics*, **70(11)**, 1946-1956.

Juma, C., 2011: *The New Harvest: Agricultural Innovation in Africa.* Oxford University Press, New York, NY, USA, 270 pp.

Kates, R.W., 2000a: Cautionary tales: adaptation and the global poor. *Climatic Change*, **45**, 5-17.

Kates, R.W., 2000b: Population and consumption: what we know, what we need to know. *Environment*, **42(3)**, 10-19.

Kates, R.W., W.N. Travis, and T.J. Wilbanks, 2012: Transformational adaptation when incremental adaptations are insufficient. *Proceedings of the National Academy of Sciences of the United States of America*, **109(19)**, 7156-7161.

Keith, D.W., 2000: Geoengineering the climate: history and prospect. *Annual Review, Energy and Environment*, **25**, 245-284.

Kemp, R., 1994: Technology and the transition to environmental sustainability: the problems of technological regime shifts. *Futures*, **26(10)**, 1023-1046.

Kingdon, J.W., 1995: *Agendas, Alternatives, and Public Policies*. 2nd edn., Addison-Wesley Educational Publishers, Inc., New York, NY, USA, 253 pp.

Klein, R., E. Schipper, and S. Dessai, 2005: Integrating mitigation and adaptation into climate and development policy: three research questions. *Environmental Science and Policy*, **8(6)**, 579-588.

Klenow, P.J. and A. Rodríguez-Clare, 2005: Externalities and growth. In: *Handbook of Economic Growth* [Aghion, A.P. and S. Durlauf (eds.)]. Vol. 1A, Elsevier B.V., Amsterdam, Netherlands, pp. 817-861.

Kok, M., B. Metz, J. Verhagen, and S. Van Rooijen, 2008: Integrating development and climate policies: national and international benefits. *Climate Policy*, **8(2)**, 103-118.

Kopytko, N. and J. Perkins, 2011: Climate change, nuclear power, and the adaptation-mitigation dilemma. *Energy Policy*, **39**, 318-333.

Kriegler, E., B.C. O'Neill, S. Hallegatte, T. Kram, R.J. Lempert, R.H. Moss, and T.J. Wilbanks, 2012: The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathways. *Global Environmental Change*, **22(4)**, 807-822.

Kristjanson, P., R.S. Reid, N. Dickson, W.C. Clark, D. Romney, R. Puskur, S. MacMillan, and D. Grace, 2009: Linking international agricultural research knowledge with action for sustainable development. *Proceedings of the National Academy of Sciences of the United States of America*, **106(13)**, 5047-5052.

Kusters, K. and N. Wangdi, 2013: The costs of adaptation: changes in water availability and farmers' responses in Punakha district, Bhutan. *International Journal of Global Warming*, **5(4)**, 387-399.

La Rovere, E.L., A.C. Avzaradel, and J.M.G. Monteiro, 2009: Potential synergy between adaptation and mitigation strategies: production of vegetable oils and biodiesel in northeastern Brazil. *Climate Research*, **40**, 233-239.

Lafferty, W.M. and J. Meadowcroft, 2010: *Implementing Sustainable Development: Strategies and Initiatives in High Consumption Societies.* Oxford University Press, New York, NY, USA, 523 pp.

Lebel, L., 2005: Carbon and water management in urbanization. *Global Environmental Change*, **15(4)**, 293-295.

Leiserowitz, A.A., R.W. Kates, and T.M. Parris, 2005: What is sustainable development? Goals, indicators, values, and practice. *Environment: Science and Policy for Sustainable Development*, **47(1)**, 8-21.

Lemos, M.C., A. Agrawal, O. Johns, D. Nelson, and N. Engle, 2013: Building adaptive capacity to climate change in less developed countries. In: *Climate Science for Serving Society: Research, Modeling and Prediction Priorities* [Asrar, G.R. and J.W. Hurrell (eds.)]. OSC Monograph Reviews, Springer Science, Dordrecht, Netherlands, pp. 437-458.

Lenton, T.M., 2011a: Early warning of climate tipping points. *Nature Climate Change*, **1**, 201-209.

Lenton, T.M., 2011b: 2 °C or not 2 °C? That is the climate question. *Nature*, **473**, 7, doi:10.1038/473007a.

Locatelli, B., V. Evans, A. Wardell, A. Andrade, and R. Vignola, 2011: Forests and climate change in Latin America: linking adaptation and mitigation in projects and policies. *Forests*, **2**, 431-450.

Loorbach, D., 2007: Governance for sustainability. *Sustainability: Science, Practice & Policy*, **3(2)**, 1-4.

Lovins, L.H. and B. Cohen, 2011: *Climate Capitalism: Capitalism in the Age of Climate Change.* Hill and Wang, New York, NY, USA, 272 pp.

MacCracken, M., 2011: Potential applications of climate engineering technologies to moderation of critical climate change impacts. In: *Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Geoengineering* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, C. Field, V. Barros, T.F. Stocker, Q. Dahe, J. Minx, K. Mach, G.-K. Plattner, S. Schlömer, G. Hansen, and M. Mastrandrea (eds.)]. Meeting held in Lima, Peru, 20-22 June 2011, IPCC Working Group III Technical Support Unit, Potsdam Institute for Climate Impact Research, Potsdam, Germany, pp. 55-56.

Malthus, T.R., 1798: *An Essay on the Principle of Population, as it Affects the Future Improvement of Society, with Remarks on the Speculations of Mr. Godwin, M. Condorcet, and Other Writers*. 1st edn., J. Johnson, London, UK, 396 pp.

Manyena, S.B., 2006: The concept of resilience revisited. *Disasters*, **30(4)**, 433-450.

Marshall, N.A., S.E. Park, W.N. Adger, K. Brown, and S.M. Howden, 2012: Transformational capacity and the influence of place and identity. *Environmental Research Letters*, **7(3)**, 034022, doi:10.1088/1748-9326/7/3/034022.

Marston, A., 2012: *One Planet – One Future: Equity and Resilience for Sustainable Development: CARE at Rio Plus 20*. CARE Denmark (CARE DK), Kobenhavn, Denmark, 27 pp.

Matthew, R.A. and A. Hammill, 2009: Sustainable development and climate change *International Affairs*, **85(6)**, 1117-1128.

McSweeney, K. and O.T. Coomes, 2011: Climate-related disaster opens a window of opportunity for rural poor in northeastern Honduras. *Proceedings of the National Academy of Sciences of the United States of America*, **108(13)**, 5203-5208.

Meadowcroft, J., 2000: Sustainable development: a new(ish) idea for a new century? *Political Studies*, **48(2)**, 370-387.

Meadowcroft, J., 2009: What about the politics? Sustainable development, transition management, and long term energy transitions. *Policy Sciences*, **42(4)**, 323-340.

Metz, B. and M. Kok, 2008: Integrating development and climate policies. *Climate Policy*, **8**, 99-102.

Metz, B., M. Berk, M. den Elzen, B. de Vries, and D. van Vuuren, 2002: Towards an equitable global climate change regime: a compatibility with Article 2 of the Climate Change Convention and the link with sustainable development. *Climate Policy*, **2(2-3)**, 211-230.

Millar, C.I., N.L. Stephenson, and S.L. Stephens, 2007: Climate change and forests of the future: managing in the face of uncertainty. *Ecological Applications*, **17(8)**, 2145-2151.

Miller, A.S., 2008: Financing the integration of climate change mitigation into development. *Climate Policy*, **2**, 152-169.

Mirza, M.M.Q., 2003: Climate change and extreme weather events: can developing countries adapt? *Climate Policy*, **3**, 233-248.

Mitchell, T., and S. Dovers, 2006: *Adapting to Climate Change: Challenges and Opportunities for the Development Community.* Institute of Development Studies (IDS), Tearfund, Teddington, UK, 36 pp.

Mitchell, T. and T. Tanner, 2006: *Overcoming the Barriers: Mainstreaming Climate Adaptation in Developing Countries.* Tearfund Climate Change Briefing Paper 1, Climate Change and Disasters Group, Institute of Development Studies (IDS), Tearfund, Teddington, UK, 28 pp.

Moed, H. and A. Plume, 2011: The multi-dimensional research assessment matrix. *Research Trends*, **(23)**, 5-7.

Monnereau, I. and S. Abraham, 2013: Limits to autonomous adaptation in response to coastal erosion in Kosrae, Micronesia. *International Journal of Global Warming*, **5(4)**, 416-432.

Morgan, J. and T. Farsides, 2009: Measuring meaning in life. *Journal of Happiness Studies*, **10**, 197-214.

Muller, B., 2009: *Additionality in the Clean Development Mechanism: Why and What?* Oxford Institute for Energy Studies, EV44, Oxford, UK, 18 pp.

Munasinghe, M., 2010: Addressing the sustainable development and climate change challenges together: applying the sustainonomics framework. *Procedia – Social and Behavioral Sciences*, **2(5)**, 6634-6640.

Naess, L.O., G. Bang, S. Eriksen, and J. Vevatne, 2005: Institutional adaptation to climate change: flood responses at the municipal level in Norway. *Global Environmental Change: Human and Policy Dimensions*, **15(2)**, 125-138.

Nelson, D.R., N. Adger, and K. Brown, 2007: Adaptation to environmental change: contributions of a resilience framework. *Annual Review of Environment and Resources*, **32(1)**, 395-419.

Nelson, R.R. and S. Winter, 1982: *An Evolutional Theory of Economic Change.* Harvard University Press, Cambridge, MA, USA, 437 pp.

Ness, B., E. Urbel-Pirsalu, S. Anderberg, and S. Olsson, 2007: Categorising tools for sustainability assessment. *Ecological Economics*, **60**, 498-508.

Netherlands Environmental Assessment Agency, 2009: *Co-Benefits of Climate Policy.* Netherlands Environmental Assessment Agency (PBL), Bilthoven, Netherlands, 72 pp.

New, M., D. Liverman, H. Schroder, and K. Anderson, 2012: Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications. *Philosophical Transactions of the Royal Society*, **369**, 6-19.

National Research Council, 1996: *Understanding Risk: Informing Decisions in a Democratic Society.* Committee on Risk Characterization, National Research Council, National Academy Press, Washington, DC, USA, 250 pp.

National Research Council, 1999: *Our Common Journey: A Transition Toward Sustainability.* Board on Sustainable Development, National Research Council, National Academies Press, Washington, DC, USA, 350 pp.

National Research Council, 2010a: *Adapting to Impacts of Climate Change.* Report of the Panel on Adapting to the Impacts of Climate Change, NAS/NRC Committee on America's Climate Choices, National Research Council, Washington, DC, USA, 292 pp.

National Research Council, 2010b: *Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia.* Committee on Stabilization Targets for Atmospheric Greenhouse Gas Concentrations, National Research Council, National Academies Press, Washington, DC, USA, 298 pp.

National Research Council, 2011: *America's Climate Choices.* Board on Atmospheric Sciences and Climate, Division on Earth and Life Studies, National Research Council, National Academies Press, Washington, DC, USA, 144 pp.

O'Brien, K., 2009: Do values subjectively define the limits to climate change adaptation? In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, N.W., J. Lorenzoni, and K. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 164-180.

O'Brien, K., 2012: Global environmental change II: from adaptation to deliberate transformation. *Progress in Human Geography*, **36(5)**, 667-676.

O'Brien, K. and R.M. Leichenko, 2003: Winners and losers in the context of global change. *Annals, Association of American Geographers*, **93(1)**, 89-103.

O'Brien, K. and L. Sygna, 2013: Responding to climate change: the three spheres of transformation. In: *Proceedings* of *Transformation in a Changing Climate, June 19-21, Oslo, Norway*. University of Oslo, Department of Sociology and Human Geography, Oslo, Norway, pp.16-23.

O'Brien, K.L., A.L. St. Clair, and B. Kristoffersen (eds.), 2010: *Toward a New Science on Climate Change.* Cambridge University Press, Cambridge, UK, pp. 215-227.

O'Hara, P.A., 2009: Climate change and political economy. *Ecological Economics*, **69**, 223-234.

Oliver-Smith, A., S.L. Cutter, K. Warner, C. Corendea, and K. Yuzva, 2012: *Addressing Loss and Damage in the Context of Social Vulnerability and Resilience.* United Nations University Institute for Environment and Human Security (UNU-EHS), Bonn, Germany, pp. 3-35.

Omolo, N., 2010: Gender and climate change-induced conflict in pastoral communities: case study of Turkana in Northwestern Kenya. *African Journal on Conflict Resolution*, **10(2)**, 81-102.

Ostrom, E., 1986: An agenda for the study of institutions. *Public Choice*, **48**, 3-25.

Park, S.E., N.A. Marshall, E. Jakku, A.M. Dowd, S.M. Howden, E. Mendham, and A. Fleming, 2012: Informing adaptation responses to climate change through theories of transformation. *Global Environmental Change*, **22**, 115-126.

Patel, P. and K. Pavit, 1995: Patterns of technological activity: their measurement and interpretation. In: *Handbook of Economics of Innovation and Technological Change* [Stone, P. (ed.)]. Blackwell Handbooks in Economics, Blackwell Publishers, Ltd., Oxford, UK, pp. 14-51.

Pelling, M., 2010: *Adaptation to Climate Change: From Resilience to Transformation.* Routledge, Abingdon, UK and New York, NY, USA, 224 pp.

Pelling, M., C. High, J. Dearing, and D. Smith, 2007: Shadow spaces for social learning: a relational understanding of adaptive capacity to climate change within organizations. *Environment and Planning A*, **40**, 867-884.

Perez, C., 2002: *Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages.* Edward Elgar, Northampton, MA, USA, 198 pp.

Peters, G.P., R.M. Andrew, T. Boden, J.G. Canadell, P. Ciais, C. Le Quéré, G. Marland, M.R. Raupach, and C. Wilson, 2013: The challenge to keep global warming below 2°C. *Nature Climate Change*, **3**, 4-6.

Pintér, L., P. Hardi, A. Martinuzzi, and J. Hall, 2011: Bellagio STAMP: principles for sustainability assessment and measurement. *Ecological Indicators*, **17**, 20-28.

Pramova, E., B. Locatelli, I.H. Djoud, and O. Somorin, 2012: Forests and trees for social adaptation to climate variability and change. *Wiley Interdisciplinary Reviews: Climate Change*, **2(1)**, 434-450.

Preston, B.L., K. Dow, and F. Berkhout, 2013: The climate adaptation frontier. *Sustainability*, **5(3)**, 1011-1035, doi:10.3390/su5031011.

Pyke, C.R., B.G. Bierwagen, J. Furlow, J. Gamble, T. Johnson, S. Julius, and J. West, 2007: A decision inventory approach for improving decision support for climate change impact assessment and adaption. *Environmental Science & Policy*, **10(7-8)**, 610-621.

Rabbani, G., A. Rahman, and K. Mainuddin, 2013: Salinity-induced loss and damage to farming households in coastal Bangladesh. *International Journal of Global Warming*, **5(4)**, 400-415.

Rao, P.K., 2000: *Sustainable Development: Economics and Policy.* Blackwell Publishers, Ltd., Oxford, UK, 393 pp.

Raven, R., S. van den Bosch, and S. Weterings, 2010: Transitions and strategic niche management: towards a competence kit for practitioners. *International Journal of Technology Management*, **51(1)**, 57-74.

Riahi, K., 2000: Energy technology strategies for carbon dioxide mitigation and sustainable development. *Environmental Economics and Policy Studies*, **32(2)**, 89-123.

Riahi, K., S. Rao, V. Krey, C. Cho, V. Chirkov, G. Fischer, G. Kindermann, N. Nakicenovic, and P. Rafaj, 2011: RCP 8.5 – a scenario of comparatively high greenhouse gas emissions. *Climatic Change*, **109(1-2)**, 33-57.

Roberts, J.T. and B.C. Parks, 2006: *A Climate of Injustice: Global Inequality, North-South Politics, and Climate Policy.* MIT Press, Cambridge, MA, USA, 404 pp.

Robinson, J., 2004: Squaring the circle? Some thoughts on the idea of sustainable development. *Ecological Economics*, **48**, 369-384.

Robinson, J., M. Bradley, P. Busby, D. Connor, A. Murray, B. Sampson, and W. Soper, 2006: Climate change and sustainable development: realizing the opportunity. *Ambio*, **35(1)**, 2-8.

Robock, A., L. Oman, and G. Stenchikov, 2008: Regional climate responses to geoengineering with tropical and Arctic SO_2 injections. *Journal of Geophysical Research*, **113(D16)**, 27, doi:10.1029/2008JD010050.

Rockström, J., W. Steffen, K. Noone, A. Persson, F.S. Chapin III, E.F. Lambin, T.M. Lenton, M. Scheffer, C. Folke, H.J. Schellnhuber, B. Nykvist, C.A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P.K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R.W. Corell, V.J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J.A. Foley, 2009: A safe operating space for humanity. *Nature*, **461(282)**, 472-475.

Rogelj, J., D.L. McCollum, A. Reisinger, M. Meinshausen, and K. Riahi, 2013: Probabilistic cost estimates for climate change mitigation. *Nature*, **493**, 79-83.

Rohracher, H., 2008: Energy systems in transition: contributions from social sciences. *International Journal of Environmental Technology and Management*, **9(203)**, 144-161.

Romero-Lankao, P. and T.J. Wilbanks, 2011: Linkages between climate change responses, research and policy directions. In: *Global Report on Human Settlements 2011: Cities and Climate Change.* UN Human Settlements Programme (UN-HABITAT), Earthscan, London, UK and Washington, DC, USA, pp. 163-183.

Rose, S., 2010: *The Importance of Multi-metric, Scale, and Sector Climate Change Impacts Valuation*. Presentation prepared for the Energy Modeling Forum (EMF) Workshop: Climate Change Impacts and Integrated Assessment (CCIIA), July 27-August 4, Snowmass, CO, USA, emf.stanford.edu/files/docs/259/Rose7-28.pdf.

Rosenzweig, C. and F.N. Tubiello, 2007: Adaptation and mitigation strategies in agriculture: an analysis of potential synergies. *Mitigation and Adaptation Strategies for Global Change*, **12**, 855-873.

Rounsevell, M.D.A., T.P. Dawson, and P.A. Harrison, 2010: A conceptual framework to assess the effects of environmental change on ecosystem services. *Biodiversity and Conservation*, **19**, 2823-2842.

Rowe, G. and L.J. Frewer, 2004: Evaluating public participation exercises: a research agenda. *Science, Technology, and Human Values*, **29(4)**, 512-556.

Roy, M., 2009: Planning for sustainable urbanization in fast growing cities: mitigation and adaptation issues addressed in Dhaka, Bangladesh. *Habitat International*, **33(3)**, 276-286.

Saito, N., 2013: Mainstreaming climate change adaptation in least developed countries in South and Southeast Asia. *Mitigation and Adaptation Strategies for Global Change*, **18(6)**, 825-849.

Salter, J., J. Robinson, and A. Wick, 2010: Participatory methods of integrated assessment: a review. *Wiley Interdisciplinary Reviews: Climate Change*, **1**, 697-717.

Sanwal, M., 2012: Rio +20, climate change and development: the evolution of sustainable development (1972-2012). *Climate and Development*, **42(2)**, 157-166.

Scheffer, M., J. Bascompte, W.A. Brock, V. Brovkin, S.R. Carpenter, V. Dakos, H. Held, E.H. van Nes, M. Rietkerk, and G. Sugihara, 2009: Early-warning signals for critical transitions. *Nature*, **461**, 53-59.

Schipper, L., 2007: *Climate Change Adaptation and Development: Exploring the Linkages*. Working Paper No. 107, Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, UK, 13 pp.

Schipper, L. and M. Pelling, 2006: Disaster risk, climate change and international development: scope for, and challenges to integration. *Disasters*, **30(1 SI)**, 19-38.

Schlager, E. and T. Heikkila, 2011: Left high and dry? Climate change, common pool resource theory and the adaptability of western water compacts. *Public Administration Review*, **71(3)**, 461-470.

Schlitz, M.M., C. Vieten, and E.M. Miller, 2010: Worldview transformation and the development of social consciousness. *Journal of Consciousness Studies*, **17(7-8)**, 18-36.

Schneider, S., 1996: Geoengineering: could – or should – we do it? *Climatic Change*, **33**, 291-302.

Schneider, S., 2008: Geoengineering: could we or should we make it work? *Philosophical Transactions of the Royal Society A*, **366**, 3843-3862.

Schoolmaster, D.R., J.B. Grace, E.W. Schweiger, G.R. Guntenspergen, B.R. Mitchell, K.M. Miller, and A.N. Little, 2013: An algorithmic and information-theoretic approach to multimetric index construction. *Ecological Indicators*, **26**, 14-23.

Scrieciu, S., T. Barker, and F. Ackerman, 2013: Pushing the boundaries of climate economics: critical issues to consider in climate policy analysis. *Ecological Economics*, **85**, 155-165.

Seballos, F. and S. Kreft, 2011: Towards an understanding of the political economy of the PPCR. *IDS Bulletin*, **42(3)**, 33-41.

Sen, A., 1999: *Development as Freedom.* Alfred A. Knopf, Inc., New York, NY, USA, 366 pp.

Senaratne, A. and K. Wickramasinghe, 2010: Climate change, local institutions and adaptation experience: the village tank farming community in the dry zone of Sri Lanka. In: *Proceedings of the National Conference on Water, Food Security, and Climate Change in Sri Lanka, BMICH, Colombo, June 9-11, 2009: Volume 2. Water Quality, Environment, and Climate Change* [Evans, A. and K. Jinapala (eds.)]. International Water Management Institute (IWMI), Battaramulla, Sri Lanka, pp. 147-174.

Seto, K.C., R. Sanchez-Rodriguez, and M. Fragkias, 2010: The new geography of contemporary urbanization and the environment. *Annual Review of Environment and Resources*, **35**, 167-194.

Shah, T., 2009: Climate change and groundwater: India's opportunities for mitigation and adaptation. *Environmental Research Letters*, **4(3)**, 035005, doi:10.1088/1748-9326/4/3/035005.

Sheppard, S. and M. Meitner, 2005: Using multi-criteria analysis and visualization for sustainable forest management planning with stakeholder groups. *Forest Ecology and Management*, **207(1-2)**, 171-187.

Shove, E. and G. Walker, 2010: Governing transitions in the sustainability of everyday life. *Research Policy*, **39**, 471-476.

Sietz, D., M. Boschütz, and R.J.T. Klein, 2011: Mainstreaming climate adaptation into development assistance: rationale, institutional barriers and opportunities in Mozambique. *Environmental Science & Policy*, **14(4)**, 493-502.

Sitarz, D. (ed.), 1994: *Agenda 21: The Earth Summit Strategy to Save our Planet.* EarthPress, Boulder, CO, USA, 321 pp.

Smit, B. and O. Pilifosova, 2001: Adaptation to climate change in the context of sustainable development and equity. In: *Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of the Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 879-912.

Smit, B. and J. Wandel, 2006: Adaptation, adaptive capacity and vulnerability. *Global Environmental Change*, **16(3)**, 282-292.

Smith, A. and A. Stirling, 2010: The politics of social-ecological resilience and sustainable socio-technical transitions. *Ecology and Society*, **15(1)**, 11, www.ecologyandsociety.org/vol15/iss1/art11/.

Smith, J.B., S.H. Schneider, M. Oppenheimer, G.W. Yohe, W. Hare, M.D. Mastrandrea, A. Patwardan, I. Burton, J. Corfee-Morlot, C.H.D. Magadza, H.-M. Füssel, A.B. Pittock, A. Rahman, A. Suarez, and J.-P. vanYpersele, 2009: Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) "reasons for concern". *Proceedings of the National Academy of Sciences of the United States of America*, **106**, 4133-4137.

Smith, M., L. Horrocks, A. Harvey, and C. Hamilton, 2011: Rethinking adaptation for a 4°C world. *Philosophical Transactions of the Royal Society A*, **369(1934)**, 196-216.

Sosa-Rodriguez, F.S., 2013: From federal to city mitigation and adaptation: climate change policy in Mexico City. *Mitigation and Adaptation Strategies for Global Change*, doi:10.1007/s11027-013-9455-1.

Stafford, S.G., D.M. Bartels, S. Begay-Campbell, J.L. Bubier, J.C. Crittenden, S.L. Cutter, J.R. Delaney, T.E. Jordan, A.C. Kay, G.D. Libecap, J.C. Moore, N.N. Rabalais, D. Rejeski, O.E. Sala, J.M. Shepherd, and J. Travis, 2010: Now is the time for action: transitions and tipping points in complex environmental systems. *Environment*, **52(1)**, 38-45.

Stern, P.C. and T. J. Wilbanks, 2009: Appendix D: Fundamental research priorities to improve the understanding of human dimensions of global change. In: *Restructuring Federal Climate Research to Meet the Challenges of Climate Change*. Committee on Strategic Advice on the U.S. Climate Change Science Program, Division on Earth and Life Studies, Division of Behavioral and Social Sciences and Education, National Research Council, National Academies Press, Washington, DC, USA, pp. 167-202.

Stoorvogel, J.J., J.M. Antle, C.C. Crissman, and W. Bowen, 2004: The tradeoff analysis model: integrated bio-physical and economic modeling. *Agricultural Systems*, **80**, 43-66.

Stringer, L.C., J.C. Dyer, M.S. Reed, A.J. Dougill, C. Twyman, and D. Mkwambisi, 2009: Adaptations to climate change, drought and desertification: local insights to enhance policy in Southern Africa. *Environmental Science & Policy*, **12(7)**, 748-765.

Sutter, C. and J.C. Parreño, 2007: Does the current Clean Development Mechanism (CDM) deliver its sustainable development claim? An analysis of officially registered CDM projects. *Climatic Change*, **84**, 75-90.

Swart, R. and F. Raes, 2007: Making integration of adaptation and mitigation work: mainstreaming into sustainable development policies? *Climate Policy*, **7**, 288-303.

Swart, R., J. Robinson, and S. Cohen, 2003: Climate change and sustainable development: expanding the options. *Climate Policy*, **3(Suppl. 1)**, S19-S40.

Tanner, T. and J. Allouche, 2011: Towards a new political economy of climate change and development. *IDS Bulletin*, **42(3)**, 1-14, doi: 10.1111/j.1759-5436.2011.00217.x.

Tejero, I.G., V.H.D. Zuazo, J.A.J. Bocanegra, and J.A.L. Fernández, 2011: Improved water-use efficiency by deficit irrigation programmes: implications for saving water in citrus orchards. *Scientia Horticulturae*, **128(3)**, 274-282.

Thomalla, F., T. Downing, E. Spanger-Siegfried, and G. Han, 2006: Reducing hazard vulnerability: towards a common approach between disaster risk reduction and climate adaptation. *Environment*, **30(1)**, 39-48.

Thomas, D.S.G. and C. Twyman, 2005: Equity and justice in climate change adaptation amongst natural-resource-dependant societies. *Global Environmental Change*, **15(2)**, 115-124.

Tol, R.S.J., 2004: Adaptation and mitigation: trade-offs in substance and methods. *Environmental Science and Policy*, **8**, 572-578.

Tompkins, E.L. and W.N. Adger, 2004: Does adaptive management of natural resources enhance resilience to climate change? *Ecology and Society*, **9**, 2-10.

Tompkins, E.L., M.C. Lemos, and E. Boyd, 2008: A less disastrous disaster: managing response to climate-driven hazards in the Cayman Islands and NE Brazil. *Environmental Change*, **18(4)**, 736-745.

Traore, S. and T. Owiyo, 2013: Dirty droughts causing loss and damage in Northern Burkina Faso. *International Journal of Global Warming*, **5(4)**, 498-513.

Turner, W.R., B.A. Bradley, L.D. Estes, D.G. Hole, M. Oppenheimer, and D.S. Wilcove, 2010: Climate change: helping nature survive the human response. *Conservation Letters*, **3(5)**, 304-312.

UK Royal Society, 2009: *Geoengineering the Climate: Science, Governance, and Uncertainty.* The Royal Society, London, UK, 82 pp.

UN-REDD Programme, 2013: *UN-REDD Programme*, *Multiple Benefits*. United Nations Environment Programme (UNEP), United Nations (UN) collaborative initiative on Reducing Emissions from Deforestation and forest Degradation (REDD) in developing countries, UN-REDD Programme, UN-REDD Programme Secretariat, Geneva, Switzerland.

UNFCCC, 2011: *Assessing the Costs and Benefits of Adaptation Options: An Overview of Approaches.* United Nations Framework Convention on Climate Change (UNFCCC), UNFCCC Secretariat, Bonn, Germany, 48 pp.

Vaughan, N. and T. Linten, 2011: A review of climate geoengineering proposals. *Climatic Change*, **109**, 745-790.

Veeman, T.S. and J. Politylo, 2003: The role of institutions and policy in enhancing sustainable development and conserving natural capital. *Environment, Development and Sustainability*, **5**, 317-332.

Vergara, W., A.R. Rios, L.M. Galindo, P. Gutman, P. Isbell, P. Suding, A. Grunwaldt, A. Deeb, J. Samaniego, E. Allatorre, and M. Panuncio, 2012: *The Climate and Development Challenge for Latin America and the Caribbean: Options for Climate-Resilient, Low-Carbon Development.* Inter-American Development Bank (IADB) in collaboration with the Economic Commission of Latin America and the Caribbean (ECLAC) and the World Wildlife Fund (WWF), IADB, Washington, DC, USA, 103 pp.

Victor, P., 2008: *Managing Without Growth: Slower by Design, Not Disaster.* Edward Elgar, Cheltenham, UK and Northampton, MA, USA, 272 pp.

Victor, P. and G. Rosenbluth, 2007: Managing without growth. *Ecological Economics*, **61**, 492-504.

Viguié, V. and S. Hallegatte, 2012: Trade-offs and synergies in urban climate policies. *Nature Climate Change*, **5**, 334-337.

Von Bernard, H. and M. Gorboran, 2010: Causes for unsustainability. *Ecología Austral*, **20(3)**, 303-306.

Walker, B. and D. Salt, 2006: *Resilience Thinking: Sustaining Ecosystems and People in a Changing World.* Island Press, Washington, DC, USA, 174 pp.

Warner, K. and T. Afifi, 2013: Where the rain falls: evidence from 8 countries on how vulnerable households use migration to manage the risk of rainfall variability and food insecurity. *Climate and Development* (in press), doi:10.1080/17565529.2013.835707.

Warner, K. and K. van der Geest (eds.), 2013: Loss and damage from climate change: local-level evidence from nine vulnerable countries. *International Journal of Global Warming*, **5(4)**, 367-386.

Warner, K., S. Kreft, M. Zissener, P. Höppe, C. Bals, T. Loster, J. Linnerooth-Bayer, S. Tschudi, E. Gurenko, A. Haas, S. Young, P. Kovacs, A. Dlugolecki, and A. Oxley, 2012a: *Insurance Solutions in the Context of Climate Change-Related Loss and Damage.* Policy Brief No. 6, The Munich Climate Insurance Initiative (MCII), hosted by the United Nations University Institute for Environment and Human Security (UNU-EHS), UNU-EHS, Bonn, Germany, 48 pp.

Warner, K., K. van der Geest, S. Kreft, S. Huq, S. Harmeling, K. Kusters, and A. de Sherbinin, 2012b: *Evidence from the Frontlines of Climate Change: Loss and Damage to Communities Despite Coping and Adaptation*. Loss and Damage in Vulnerable Countries Initiative, Policy Report No. 9, United Nations University Institute for Environment and Human Security (UNU-EHS), UNU-EHS, Bonn, Germany, 86 pp.

Washington, W.M., R. Knutti, G.A. Meehl, H. Teng, C. Tebaldi, D. Lawrence, J. Buja, and W.G. Strand, 2009: How much climate change can be avoided by mitigation? *Geophysical Research Letters*, **36(8)**, L08703, doi:10.1029/2008GL037074.

WCED, 1987: *Our Common Future.* Report of the World Commission on Environment and Development, Annex to General Assembly document A/42/427, Development and International Co-operation: Environment, World Commission on Environment and Development (WCED), Oxford University Press, London, UK, 383 pp.

Westley, F., P. Olsson, C. Folke, T. Homer-Dixon, H. Vredenburg, D. Loorbach, J. Thompson, M. Nilsson, E. Lambin, J. Sendzimir, B. Banerjee, V. Galaz, and S. van der Leeuw, 2011: Tipping toward sustainability: emerging pathways of transformation. *Ambio*, **40(7)**, 762-780.

WHO, 2011: *Health in the Green Economy: Health Co-Benefits of Climate Change Mitigation –Transport Sector* [Hosking, J., M. Pierpaolo, and C. Dora, (eds.)]. World Health Organization (WHO), Geneva, Switzerland, 144 pp.

Wilbanks, T.J., 2003: Integrating climate change and sustainable development in a place-based context. *Climate Policy*, **3(Suppl. 1)**, S147-S154.

Wilbanks, T.J., 2009: *How Geographic Scale Matters in Seeking Community Resilience.* CARRI Research Paper No. 7, Community and Regional Resilience Initiative (CARRI), Oak Ridge, TN, USA, 13 pp.

Wilbanks, T.J., 2010: Inducing transformational energy technological change. *Energy Economics*, **33(4)**, 699-708.

Wilbanks, T.J. and R.W. Kates, 2010: Beyond adapting to climate change: embedding adaptation in responses to multiple threats and stresses. *Annals Association of American Geographers*, **100(4)**, 719-728.

Wilbanks, T.J. and J. Sathaye, 2007: Integrating mitigation and adaptation as responses to climate change: a synthesis. *Mitigation and Adaptation Strategies for Global Change*, **12**, 957-962.

Wilbanks, J.T. and T.J. Wilbanks, 2010: Science, open communication, and sustainable development. *Sustainability*, **2(4)**, 993-1015.

Wilbanks, T.J., P. Leiby, R.D. Perlack, J.T. Ensminger, and S.B. Wright, 2007: Toward an integrated analysis of mitigation and adaptation: some preliminary findings *Mitigation and Adaptation Strategies for Global Change*, **12(5)**, 713-725.

Wilson, C. and T. McDaniels, 2007: Structured decision-making to link climate change and sustainable development. *Climate Policy*, **7(4)**, 353-370.

Winkelman, A.G. and M.R. Moore, 2011: Explaining the differential distribution of Clean Development Mechanism projects across host countries. *Energy Policy*, **39**, 1132-1143.

Winkler, H., K. Baumert, O. Blanchard, S. Burch, and J. Robinson, 2007: What factors influence mitigative capacity? *Energy Policy*, **35**, 692-703.

Wolf, J., K. Brown, and D. Conway, 2009: Ecological citizenship and climate change: perceptions and practice. *International Politics*, **18(4)**, 467-485.

World Bank, 2010: *World Development Report: Development and Climate Change.* The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 417 pp.

Xiong, W., L. Holman, and E.D. Lin, 2010: Climate change, water availability, and future cereal production in China. *Agriculture, Ecosystems, and Environment*, **135**, 58-69.

Yaffa, S., 2013: Coping measures not enough to avoid loss and damage from drought in the North Bank region of the Gambia. *International Journal of Global Warming*, **5(4)**, 467-482.

Yohe, G., 2001: Mitigative capacity: the mirror image of adaptive capacity on the emissions side. *Climatic Change*, **49**, 247-262.

Yohe, G., 2012: Economics and environmental studies. *Review of Development Economics*, **16(3)**, 503-510.

Yohe, G. and R. Tol, 2002: Indicators for social and economic coping capacity: moving toward a working definition of adaptive capacity. *Global Environmental Change*, **12**, 25-40.

Younger, M., H.R. Morrow-Almeida, S.M. Vindigni, and A.L. Dannenberg, 2008: The built environment, climate change, and health: opportunities for co-benefits. *American Journal of Preventive Medicine*, **35(5)**, 517-526.

Ziervogel, G. and A. Opere (eds.), 2010: *Integrating Meteorological and Indigenous Knowledge-Based Seasonal Climate Forecasts in the Agricultural Sector: Lessons from Participatory Action Research in Sub-Saharan Africa.* Climate Change Adaptation in Africa (CCAA) Learning Paper, International Development Research Centre (IDRC), Ottawa, ON, Canada, 19 pp.

Zou, X., Y. Li, Q. Gao, and Y. Wan, 2012: How water saving irrigation contributes to climate change resilience: a case study of practices in China. *Mitigation and Adaptation Strategies for Global Change*, **17(2)**, 111-132.